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ASSESSMENT OF GLINT HAZARD TO SOLDIERS

William J. Chevalier

December 1998

Final Report

October 1997 - September 1998

Approved for public release, distribution unlimited

U.S. Army Soldier and Biological Chemical Command
Soldier Systems Center, Natick MA 01760-5000

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The future dismounted soldier operating in a battlefield environment could be at increased risk of revelation due to the fact that he will be carrying more optical equipment thereby increasing the number of reflecting surfaces exposed to enemy surveillance. The risk level can directly relate to the extent of the visual domain size (observer space of reflecting source) that is dependent on solar environmental conditions, reflectivity optics, surveillance source(s), and counter-surveillance sources. Soldier location significance to the enemy directly influences the level of soldier risk of revelation to the enemy. Given that the risk of revelation and subsequent consequences to the soldier will be increasing over the near to mid-term, the reduction of signature size and resolution is paramount. This need is being met by installing anti-reflection devices and applying anti-reflection coatings to all optical surfaces of equipment in question without seriously reducing functionality. In addition, overall signature reduction technologies are being developed and applied to reduce the soldier signature in general. The development and application of evolving counter-surveillance technologies to reduce dismounted soldier optical and overall signature are directly influenced by the enemy's use of evolving surveillance technologies.

In all probability, the dismounted soldier location-detection and signature definition resulting from glint reflection will insignificantly affect overall soldier survivability in the battlefield. However, the ability to minimize the glint hazard is a step in the right direction to help reduce the overall soldier signature and thus reduce the probability of detection.

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Preface

This study was funded from October 1997 through September 1998 by the US Army Soldier Systems Command's Science & Technology and Survivability Directorates' AH98 programs, to see if the survivability of the soldier may be impacted by high intensity (glint) reflections from the optical surfaces of equipment employed in the current or planned for the future battlefield environment.

Recent battlefield events have raised the issue of the soldier facing additional risk of becoming a casualty due to glint signature from the optical surfaces of his equipment. During the gulf war in 1990, soldiers aboard Army Family of Vehicles (AFVs) wore goggles to shield their eyes from the dust raised by the movement of armored formations. Glints were observed off these goggles several kilometers distance.

Glint hazard to the dismounted soldier was assessed to determine the potential for revealing a soldier's location to the enemy and the subsequent impacts on soldier survivability in the battlefield environment. The hazard arises mainly from the glint reflections from the optical surfaces of eye armor, scopes, weapon and other equipment.

The author would like to extend his appreciation to Mr. Roger Schlepper, Dean Sutherland, and particularly to Mr. David Tucker and Dr. Paul D. Leitch, all Operations Research Analysts of the Modeling and Analysis Team, SBCCOM, for their constructive editing of this report.

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ASSESSMENT OF GLINT HAZARD TO SOLDIERS

SUMMARY

A literature review was performed to identify the extent of the glint hazard to the United States dismounted soldier on the battlefield in current and potential conflicts and to analyze the probable impact of the glint hazard on soldier survivability. Glint is a gleam, glimmer, sparkle or flash that can be observed during day or night under the right environmental conditions. It is a high intensity reflection of electromagnetic energy off of a smooth mirror-like surface as opposed to a diffuse or scattered reflection off of a rough, reflecting surface.

Recent battlefield events have raised the issue of risk of revealing the soldier's location by the enemy due to optical signatures. During the Gulf War in 1990, soldiers aboard various combat vehicles wore goggles to shield their eyes from the dust raised by the movement of armored formations. Glints were observed from these goggles and other soldier carried optics several kilometers from the vehicles. Thus concern exists about the hazards of high reflectance characteristics of optical surfaces on many electro-optical and visual aided devices used by the dismounted soldier.

The U.S. Army has developed an Operational Requirements Document for combat soldiers to have the ability to inhibit off-axis reflection (glint) produced by optical systems used in their missions. This requirement can be met with an Anti-reflection Device (ARD) capability. The anti-reflection device(s) will be used in conjunction with the M22 binocular, XM24 mini-binocular, M24 Sniper Day Scope, M144 Telescope and the AN/PVS-10, Sniper Day/Night Sight to satisfy present and future needs. However, neither the OCR nor any other requirements type of document in place addresses the hazard produced by glint reflection off of eye armor. In fact, glint from eye armor, visors, and similar equipment has never been considered a significant threat issue.

The glint hazard assessment focused on defining the contributions of glint relative to other detection hazards in the battlefield environment to revealing and identifying soldier position to the enemy. Also, emphasis was placed on reducing glint hazard to the soldier using present and evolving anti-reflection and coating technologies.

This study has concluded that:

1). The relative contribution of glint to the enemy's awareness of the dismounted soldier in the battlefield environment will be insignificant, although isolated incidences of significant glint hazard are possible.

2). The potential of glint hazard involving the dismounted soldier will increase over the long run due to more optical equipment that the soldier will be carrying, but should be significantly reduced through the application of anti-reflection technologies.

3). The probability of detecting the glint source will be directly influenced by such factors as a) counter-surveillance technologies, c) solar-environmental conditions, d) surveillance technologies, and e) significance of target.

4). Evolving enemy active and passive sensor surveillance technologies will contribute more significantly as a major player towards augmenting enemy awareness of the soldier's position, primarily due to improvements in and applications of three dimensional (3D) imaging, which enhances resolution and range capability.

ASSESSMENT OF GLINT HAZARD TO SOLDIERS

1. INTRODUCTION

The study was conducted to address the concern that the occurrence of glint may have a significant impact on dismounted soldier survivability.

1.1 BACKGROUND

Glint hazard to the individual soldier, due to specular reflections from the surfaces of goggles, scopes, weapons and other equipment, has never been assessed to determine the level of impact on soldier survivability.

This study was funded October 1997 to September 1998 through the US Army Soldier Systems Command's Science and Technology and Survivability Directorates' AH98 programs to see if the survivability of the soldier may be impacted by glint due to equipment employed in current and future battlefield environment.

Recent battlefield events have raised the issue of the soldier facing the additional risk of being a casualty due to glint. During the gulf war in 1990, soldiers aboard Army Family of Vehicles (AFVs) wore goggles to shield their eyes from the dust raised by the movement of armored formations. Glints were observed off these goggles at several kilometers distance.

The U.S. Army has developed an Operational Requirements Document for combat soldiers to have the ability to inhibit off-axis reflection (glint) produced by manmade optical systems use in their missions. This requirement can be met with use of an Antireflection Device (ARD) capability. The antireflection device(s) will be used in conjunction with the M22 binocular, XM24 mini-binocular, M24 Sniper Day Scope, M144 Telescope and the AN/PVS-10, Sniper Day/Night Sight to satisfy present and future needs. However, neither this requirements document nor any threat document in place addresses the glint hazard produced by glint reflection off of eye armor. In fact, glint has never been considered a significant threat issue.

To satisfy increased lethality requirements, the future dismounted soldier will carry more equipment i.e. goggles, scopes, binoculars, head-mounted display, etc., out to the battlefield with the consequence of producing more glint types of reflections, thus increasing the glint hazard level. This condition increases the risk of detection and emphasizes the need for using counter-surveillance anti-reflection technologies, i.e., mechanical devices, coatings, to the optically reflecting surfaces to counter this increased risk.

Because of the technological advances in digital battlefield applications, sensors may be embedded in the future soldier's clothing ensembles to monitor and report physiological states (e.g. blood pressure, blood oxygen, skin temperature). The addition of embedded sensors will help reduce the impacts of casualty on medical logistics personnel. However, the embedded sensors should be designed to prevent reflection of energy, to result with no change in soldier signature definition.

1.2 OBJECTIVE

The objective of this study was to assess the hazard of glint to the individual dismounted soldier operating in a spectrum of current and potential conflicts, and to identify and analyze the impact on soldier survivability.

1.3 APPROACH

A literature search was conducted to disclose the nature and extent of the glint hazard on the ability of the dismounted soldier to accomplish his mission. The study focused on defining the glint hazard associated with soldier carried optics, supported by literature covering a) historical accounts, b) surveillance and counter-surveillance technologies, and c) significance of the soldier's location to the enemy. Military considerations of glint were discussed, including an operational requirements document that addressed the need for the application of optical surface anti-reflection technology on optical surfaces of equipment carried by the soldiers, but disregarded goggles. The physics of the nature of glint was extensively defined, including the concept of the glint visual domain, as influenced by the optical properties of reflecting surfaces and the solar environmental conditions. Emphasis was placed on the risk to the soldier associated with the number and types of optical equipment that would likely be carried in the current and future battlefield environment.

The glint hazard assessment focused on the impacts of soldier equipment, visual domain, active and passive surveillance, sensor perceptibility and discriminability, counter-surveillance, and soldier location significance towards soldier risk of revelation. The study concluded with an analysis of the relative contributions of surveillance technologies and glint reflection towards enemy awareness of soldier location on the battlefield. Concepts involving glint visual domain, probability of detection, detection time, soldier location significance to enemy, counter-surveillance influence on signature reduction, and optical and electronic surveillance, were used extensively throughout the glint assessment process.

1.4 ASSUMPTIONS

The following assumptions provided the basis for this study:

1) The glint hazard of revelation corresponds to the level of significance of the soldier's location unknown to the enemy.

2) Detection, recognition, identification and discrimination processes, using the aided and unaided eye, provide a target definition and a basis for military action.

3) An extended glint threshold domain, which increases the probability of being observed, is due to

a) a reduction in atmospheric extinction effects on signature transmission,
b) optical surfaces with higher reflection characteristics,
c) optical augmentation through active and passive sensor surveillance configurations,
d) favorable solar-environmental conditions, and
e) soldier movement.

4) Evolving anti-reflection and other signature reduction technologies should reduce glint reflection off of current and future optical surfaces and decrease overall soldier signature.

5) Surveillance and counter-surveillance technologies will continue to drive each other and improve over the long run.

2. GLINT HAZARD ISSUE

Glint is a term synonymous with specular reflection. Glint is a gleam, glimmer, sparkle or flash that can be observed during day or night under the right environmental conditions. It is a high intensity reflection of electromagnetic energy off of a smooth mirror-like surface as opposed to a diffuse or scattered reflection off of a rough, reflecting surface.

Under the right environmental conditions, glint is capable of being seen out to several kilometers with the unaided eye. These conditions include a) daytime bright sunlight with little to no cloud cover, b) minimal atmospheric extinction due to low humidity and other particulate levels, c) open terrain, and d) high reflectivity surfaces. Glint is visually observed by the unaided eye as an intensity image that contrasts with a background's reflection of energy. In order for glint to be observed, there must be an optical path of solar energy transmission made up of the sun, a specular reflecting source, background reflection and observer.

Visual glint is the observance of glint by the unaided and aided eye. A glint visual domain is a visual region bounded by observer positions at respective radial distances from the reflecting source over a range of reflecting angles where glint is barely discernible with the background. The size and extent of the domain are largely a function of the effects of solar environmental conditions i.e. atmospheric extinction, etc., optical properties of the reflecting surface, and the extent of sunlight. Atmospheric extinction is the loss of light energy as it is scattered out of the beam of reflected light or absorbed by the molecular and particle constituents of the atmosphere. The domain can be extended by using binoculars, scopes, thermal imagers, visual and infrared laser radar, microwave radar, and other imagers. The domain is diminished at night since the lunar illuminance levels of a full moon are approximately 6 orders of magnitude lower than under full sunlight conditions.

Once a glint has been detected by the enemy, the reflecting source must go through a process of target recognition and identification. If the glint source is the dismounted soldier, there is a risk of being a casualty subject to the enemy's will and threat capability. Extending the visual threshold domain by using optical augmentation and signature recognition devices under optimal solar environmental conditions vastly increases the chances that more soldiers could be revealed and susceptible to casualty. In theory, as the domain extends, observers can view reflections out to greater threshold (minimally discernible) distances. This means that the probability of the enemy observer detecting the soldier (reflecting source) would increase to successively higher levels over same intervals of time for successively shorter observer distances from the threshold distance. Depending on the scenerio, there is population density level of soldiers such that the larger the visual domain the more soldiers would be at risk.

The dismounted soldier operating in the future battlefields may be at greater risk of revelation to the enemy, according to PM Soldier, since the soldier will be carrying optical equipment, eye armor, weapon system and head gear. The future soldier's equipment will most likely be designed with more optical surfaces that will be exposed to sunlight and illuminating electromagnetic energy emitted by enemy active surveillance systems. A counter-surveillance capability that will substantially reduce glint reflection off of soldier carried optics will be the use of antireflection technologies, including mechanical attachments.

2.1 SOLDIER-CARRIED OPTICS

The ability to remain undetected is essential to a soldier's survival and a successful mission. For that reason no modern military force would deploy into the field without first assessing the significance of the detection of the troop's location and taking appropriate action.

However, the proliferation of optical devices along with other specular reflection equipment used by the dismounted soldier in the battlefield environment presents a potential for him to be exposed to significant glint hazard levels, depending on mission requirements versus enemy capability and threats. Yet technology driven optical systems are essential for battlefield use, because they provide high-quality images across the visual and infrared spectral region, and in some cases protect the soldier from laser effects. Unfortunately, these same optics have the ability to divulge the location of the soldier carrying them, because of the potential for glint reflection from their reflecting surfaces.

The signature can be generated either by a retro-reflection of energy off of a focal plane internal to the optical system, or from energy reflecting off of the optical system's external surface i.e., field binoculars, scopes, thermal sights, eye armor, etc.

Overall, the level of glint hazard to the dismounted soldier, given favorable environmental conditions, is due to the assemblage of reflectance optics that enhance exposure to active and passive enemy sensor surveillance systems, including the unaided eye. This hazard is enhanced because the soldier operating from the present to the long term will carry more optical equipment, offering more reflecting sources to the enemy surveillance sensors. The equipment may include binoculars, scopes, night sights, ballistic and laser protection goggles, etc.

The enemy's major ability to enhance awareness of soldier location lies in constantly improving surveillance capability. This is driven by advances in signature resolution technologies and the relative ease of technology transfer of active and passive surveillance equipment to any country.

2.2 SUPPORT DOCUMENTATION

A literature search was performed to gather and assess any relevant glint information that might have significant impacts on soldier survivability and mission objectives in the current and future battlefield environments.

The search discerned only isolated instances during prior historical battles where solar visual glint was a factor when the presence of the enemy was revealed resulting with subsequent casualties and compromise of mission. Recent literature describes advances in electronic sensor surveillance technologies and the enemy's ability to exploit their use through technology transfers and stealth operations as early as the next decade, for enhancing the situational awareness of the soldier on the future battlefield. Yet, according to the laser lab personnel, SBCCOM, antireflection and coating applications to optical surfaces of equipment used by the dismounted soldier in combat will all but wipe out any potential solar, infrared and microwave glint consequences, as this technology is presently being exploited by our military. These anti-reflection applications to optical surfaces will tend to reduce signature definition across the visual, infrared and microwave regions, which will reduce the effectiveness of surveillance technology applications. Further reduction of signature definition can be accomplished by materiel additions to the non-glint signature surfaces of the target source to help reduce the soldier aggregate signature, which is not within the scope of this report.

2.2.1 HISTORICAL ACCOUNTS

Recent events have raised the issue of potential survivability problems due to optical signatures. During the Gulf War in 1990, soldiers aboard AFVs wore goggles to shield their eyes from the dust raised by the movement of armored formations. Glints were observed off these goggles at several kilometers distance from the vehicles. According to the laser lab personnel, SBCCOM, concern exists about the high reflectance characteristics of the optical surfaces of many electro-optical and visual devices. Earlier goggle models were noted to have optical reflectivity values up to 85% of incident energy.

According to an article "GLINT: A Soldier Survivability Issue" which appeared in MANPRINT Quarterly, 1994, written by Beth Redden, US Army Research Laboratory, she was concerned that operational requirements literature addressing soldier survivability does not seem to include glint as a survivability issue. "How many times has glint from soldier optical devices or other equipment given away their positions and led to engagements by the enemy? Unfortunately, no one seems to have an answer to that question - even for peacetime force-on-force exercises." She referred to an examination of historical battlefield accounts found that provided some additional insights into the visual glint phenomenon. Four compelling combat accounts of target detection due to visual glint reflections illustrate the significance of reducing visual glint to enhance soldier survivability.

1. Moshe Dayan, the Israeli general, got his famous eye patch when a sniper saw reflections of the sun from his binoculars during the 1968 Arab-Israeli conflict.
2. At the battle of Stalingrad during World War II, Russia's top sniper, Vasili Zaitsev, credited with more than 200 kills, won a famous three-day duel with the German top sniper, Major Zossen, by looking for and targeting the reflection from the German's rifle scope.
3. During the 1942 battle of Guadalcanal, the Japanese army's second attack on Henderson Airfield was planned as a surprise assault from the dense jungle to the south of the field. The U.S. forces were warned about the impending attack after a member of

the 7th Marine patrol noticed a glint reflection emanating from a hilltop. The source of the reflection was a pair of binoculars held by a Japanese officer. The U.S. forces were shifted in time to repel the "surprise" attack.

4. Glint had a major impact on the results of the battle of Gettysburg. Reflections from the Confederate's equipment alerted the Union's General Warren to their position below him on "Little Round Top". The reinforcements he sent for were just able to turn the tide in that pivotal battle.

Glint is an obvious signature that can key even a marginally trained counter observer to detect troops and equipment. Reflections from optical systems or vehicle lighting can compromise operational security. Operational security means we, not the enemy, determine the time and place of engagement. The ability to remain undetected is paramount to survival and completion of the mission. Today, no military force would think of going into the field without signature camouflaging their troops and equipment. The evolving optical systems, geared for use by the present and future dismounted soldier, that produce high quality images in the visual and infrared regions of the electromagnetic spectrum, give laser and ballistics protection, can betray the soldier's position by reflecting light.

2.2.2 MILITARY CONSIDERATIONS OF GLINT

According to Beth Redden, US Army Research Laboratory, Fort Benning, Georgia, "There is no mention of visual glint in the Infantry Lessons Learned Database at Fort Benning. The soldier survivability parameter assessment list does not include visual glint under "Component II: Reduce Detectability", which assesses a system's physical signature as it affects the system's detection level by threat forces. Other signatures, such as the system's silhouette, thermal signature, olfactory signature, and acoustical signature are covered." Yet "The Soldier's Manual of Common Tasks" includes tasks for equipment camouflage. They include covering all shiny objects such as optics, weapons parts, headlights reflectors, mirrors, windshields, etc.

When using optical devices, soldiers are unable to fully comply with camouflage requirements and still be able to execute operational requirements. Thus the soldier becomes vulnerable to detection each time the soldier removes the optical covers, particularly with the use of eye armor and goggles where glint reduction technologies need to be continually emphasized as a tradeoff with its ballistics and laser protection attributes.

"Increasing lethality levels over time on the battlefield means adding a host of optical equipment to the soldier system configuration." This is according to Colonel Wilfred 'Bud' Irish, U.S. Army Program Manager for Small Arms, PM Soldier, who also said that there are seven new small arms optics initiatives being managed by his office to help satisfy the Soldier Enhancement Program Initiatives. These include; a) XM68 Close Combat Optics, b) XM 145 Machine Gun Optics, c) MK 19/0.50 cal fire control system, d) M144 sniper spotting telescope, e) XM25 Stabilized Binoculars, f) M24 Miniature Binoculars, and g) New Family of Anti-Reflection Devices. The US Army has identified a requirement to reduce glint off of dismounted soldier carried optical devices by using anti-reflection shields.

A CPI Glint Reduction for Eye Armor and Specs Proposal was written by the SBCCOM laser lab, September, 1996. The objective was to investigate technologies available for reducing glint from ballistic and laser eye armor protective lenses. The direct impact benefit is that by reducing glint the soldiers will perform their missions with lower probability of revealing their presence to the enemy.

On the 29th of August,1996 Colonel Kinnison, TRADOC Systems Manager, was given a survivability capability briefing by the Survivability Directorate, SSCOM, during which he commented on two issues of concern resulting from his duty in the gulf war. "The SPECS were not dark enough to counter the intense daytime desert sun, and glint from the SPECS was a real problem."

2.2.3 OPERATIONAL REQUIREMENTS DOCUMENT

The US Army[1] has identified a requirement written as the "Operational Requirement Document for the Anti-Reflection Device (ARD) for Optics," Army Intelligence and Security Command, Fort Belvoir, 07 Nov 1995, for combat soldiers to have the ability to inhibit off-axis reflection (glint) produced by optical systems which they use in conjunction with their missions. This requirement can be met by using an Anti-Reflection Device. The antireflection device(s) will be used in conjunction with the M22 binocular, XM24 mini-binocular, M24 Sniper Day Scope, M144 Telescope and the AN/PVS-10, Sniper Day/Night Sight to satisfy present and future needs. Also, these devices will be available for use with eye armor and goggles as anti-reflection shields.

This glint reduction application is especially significant since by adding new scopes the susceptibility of the dismounted soldier to casualty is enhanced, as there are more optical surfaces that can reflect glint signatures in the visual to millimeter wavelength region. The applicable threat for the ARD requirement is described in the Land Warrior System assessment (STA) dated August 1994.

The military is exploiting other evolving anti-reflection technologies such as moth eye etchings or deposition coatings for application on optical surfaces.

2.2.4 ANTI-REFLECTION TECHNOLOGY APPLICATION

Anti-reflection mechanical devices are designed for most optical equipment and will be used to sharply reduce detection levels by significantly reducing off-axis glint. The optics using the anti-reflection device will still offer some glint return, but only along the line of sight being observed. Optical equipment functional capabilities are minimally reduced.

Another method for reducing glint on optical surfaces is to use antireflection (AR) coatings[2]. The front surface reflectivity of uncoated optics can be computed using the refractive index (n) of the substrate.

The normal incidence reflectivity decimal value (R) is derived from the expression;

$$R = (n-1)^2/(n+1)^2$$

Typically, the normal incidence reflectivity values for visible uncoated surfaces is 3 to 4%.

By applying different anti-reflection coatings one can suppress the glint as follows:

a) uniformly, but by a small amount to 2% reflectivity across the entire visible spectrum, or
b) by a large amount to 0.3% over a small portion of the visible spectrum, or
c) by a large amount to <<0.3% at selected wavelengths.

The advantage of using the last glint reduction approach (part c) is that the reflectivity at specific wavelengths can be reduced considerably. However, depending on the AR coating design, the penalty is increased reflectivity at other wavelengths. Conversely, if one uses high reflectivity surfaces as a countermeasure for laser protection such as the number of stacks embedded in SSCOM eye armor, this significantly increases the signal strength of the glint.

Designers of many optical systems, recently fielded or under development, have made an attempt to control the directionality of glints off front surface optics such as; binocular filters, rifle scope windows, and FLIR environmental windows. The axial direction of these surfaces is specifically tilted towards the ground.

3. NATURE OF GLINT OBSERVATION

In order to observe glint, it is necessary that there be optical path alignments of the solar source, reflecting surface, and the observer; and the solar source, background reflecting source, and the observer. The observer detects a contrast ratio as a difference between the luminance of the reflecting surface and that of the background divided by the background luminance, given that the size of the reflecting glint luminance is small compared to the size of that of the extended background. Glint is observed only as a point source intensity of solar energy by the eye, since the eye cannot discern the optical cross section of the signature. The observer can view glint twinkling effects due to atmospheric turbulence, but high humidity and little or no atmospheric turbulence will tend to negate the twinkling or scintillation effects of transmitted glint.

3.1 SPECULAR REFLECTION

Specular reflection occurs when electromagnetic energy incident to a smooth reflecting surface will obey a condition where the angle of incidence equals the angle of reflection. If the reflecting surface is electromagnetically penetrable, than some of the energy is transmitted through the material at an angle of refraction relative to the normal based on the optical properties of the materiel and the incidence angle (Figure 1). At a zero angle of incidence the return energy reflects back in the direction of the source. An example of this is when an active interrogating surveillance system has its energy transmitter and receiver aligned along the same directional axis. At oblique angles, the transmitter and receiver are separate in space and not aligned along same direction axis.

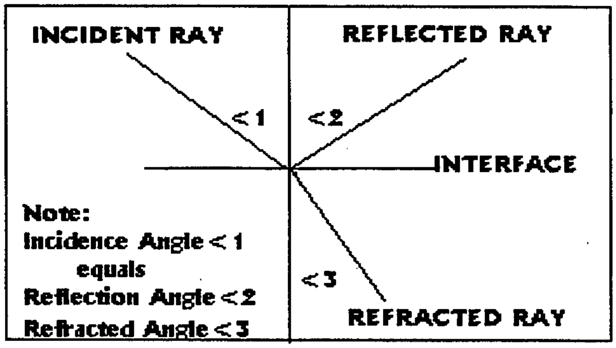

Figure 1: Specular Reflection

3.1.1 MATHEMATICAL INTERPRETATION OF SPECULAR REFLECTION

Based on the reflectivity characteristics of an optical specular surface, a statistical nonlinear fit using a 5th degree polynomial of the surface can depict a reasonably accurate statistical relationship between normalized spectrally integrated solar energy reflectivity values and solar incidence angles. This mathematical relationship can provide a basis for estimating glint threshold distances over a range of solar energy incidence angles to a reflecting surface, based on Snell's law, as applied to high reflectivity surfaces.[3] See Section 1.1.3, Appendix A.

3.1.2 GENERAL NATURE OF SURFACE REFLECTIVITY

The level of reflectivity of a surface is dependent on the a) nature of the surface i.e. glass, metal, wood, etc., b) surface texture i.e. polished, rough, etc., c) angle of incidence, d) angle of reflection, e) wavelength of light, and f) polarization of light. For optically polished, uncoated, materials such as glass, the angular dependent reflectivity can be predicted from the index of refraction.

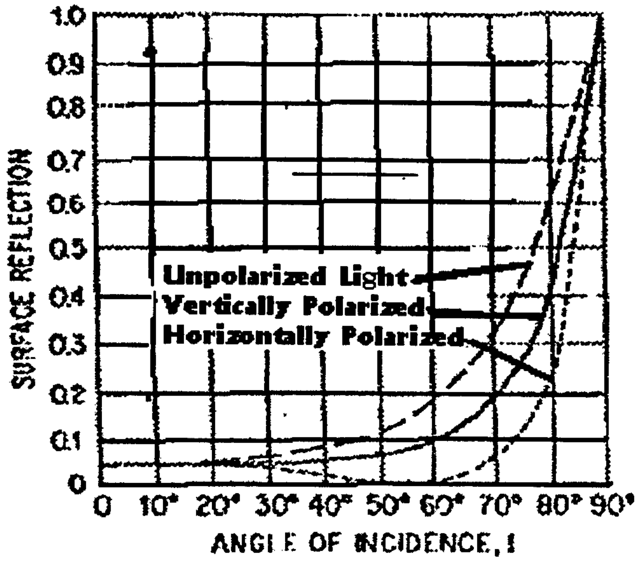

Figure 2: Normalized Reflectivity Values of C-1 Optical Glass Versus Angle of Incidence for Three Different Light Sources

An example of this angle of dependence is depicted in Figure 2. The graph shows how the reflectivity of C-1 optical glass changes as a function of incidence angle for vertical, horizontal and unpolarized lighting sources. Since glint is specular reflection, its amplitude will also follow this relationship as a function of angle. Coated optics will have their own incidence angular dependent reflectance relationships, which can be predicted using various coating reflectivity programs.

All terrestrial materials, including water, reflect light. Some materials reflect a preponderance of light that is visible to the human eye in the 400-700 nanometer wavelength range, while other materials reflect predominately infrared radiation that is observed with an infrared sensor and camera. Thus glint is not restricted to the visible region of the spectrum. Materials which are used predominantly in infrared imaging systems can have high reflectivity in the visible portion of the spectrum and as such can generate visible glint. An example of this is the germanium window used in FLIR systems. The window is opaque to the human eye of the soldier using the FLIR in the visible portion of the spectrum, thus the polished front surface acts as a metal mirror and would reflect glint that could be observed. Therefore, metallic surface paints, water and even soil have the potential of becoming a glint source with some of these materials having reflectance values that are higher than those of uncoated optical substrates.

3.2 OPTICAL PATH APPLICATION THEORY

This theory[4] is associated with the basic physical concepts involved in the attenuation of the glint spectral energy by atmospheric extinction (molecular absorption and scattering of energy) transmitted along two optical paths defined as a) sun to ground reflecting surface to observer and b) sun to background reflecting surface to observer. This theory provides a basis for calculating a loci of points that define a glint visual domain. The domain calculation is affected by atmospheric extinction levels and is based on a range of surface reflectivity coefficients of a smooth reflecting surface associated with corresponding angles of solar energy incident to a reflecting surface. Figure 3 depicts an observer to background optical path definition, while Figure 4 depicts two domains where the R(1) reflectivity coefficients have a higher set of values over a corresponding range of solar incidence/reflection angles than do the R(2) reflectivity coefficients.

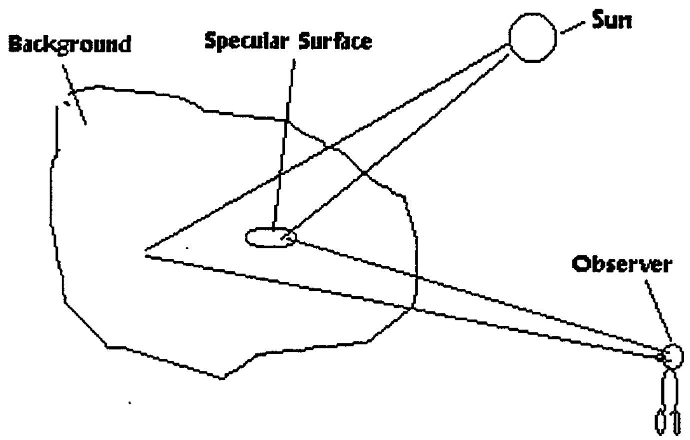

Figure 3. Sun to Specular Surface and Background Optical Paths

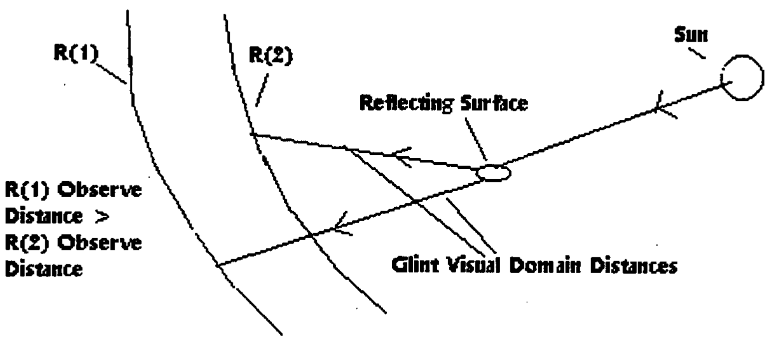

Figure 4. Pictorial of Glint Visual Threshold Domains Based on Two Sets of Specular Surface Reflectivity Coefficients R(1) and R(2), Wavelength and Solar Incidence Angle Dependent

An observer standing on the locus of points that define the edges of a domain barely discerns the glint from the reflecting source relative to the background. Modifications to the glint threshold distances due to changes in a) the optical properties of the specular surface over the range of the solar incidence angles, b) the atmospheric extinction coefficient and c) the elevation angle of the sun, will result with a corresponding change in the glint visual threshold domain definition. See Appendix A, "Development of Glint Threshold Distance Model".

3.2.1 OPTICAL PATH DEGRADATION AND FILTERING

The overall attenuation effects on transmitted solar energy along the optical paths are defined in terms of atmospheric degradation due to selective absorption, scattering and scintillation modulation.

3.2.1.1 ATMOSPHERIC DEGRADATION

There are three atmospheric processes responsible for the degradation of the transmission of optical images or signatures and electromagnetic energy intensity: aerosol extinction, molecular absorption and turbulent distortion (glint scintillation and beam wandering-twinkling stars). For further details refer to Section 1.1.4 of Appendix A, "Atmospheric Extinction Effects".

Atmospheric extinction and molecular absorption effects are clearly indicated in Figure 5 as the solar visual to near infrared energy is transmitted through the thickness of the atmosphere with the sun at the zenith point. Water vapor has some effect on solar visual energy transmission, but more so in the infrared region. Aerosol and other particulates which are not depicted contribute significantly to optical signature and intensity degradation over transmitted distances in the atmosphere.

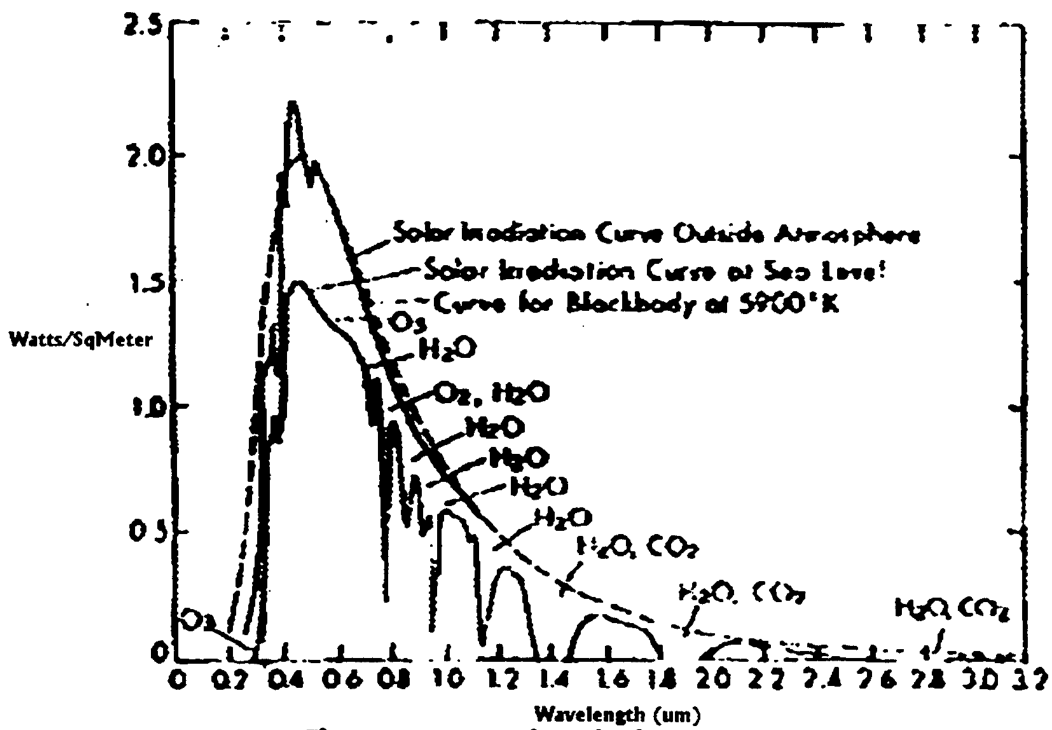

Figure 1: Atmospheric Extinction Solar Spectral Energy

Figure 5: Solar Spectral Radiance at Mean Earth Sun Separation

The propagating energy wave front, whether single or broadband wavelength(s), is modulated at some level by randomized atmospheric noise turbulence creating levels of scintillation[5], which directly correlate with the levels of atmospheric turbulence. To an observer visually reading the reflected energy sensor results, the perception response is one of twinkling. The twinkling of glint reflection will tend to lower the observer detection time somewhat, depending on the twinkling amplitude. However, increased levels of atmospheric humidity tend to lower the level of noise modulation or twinkling.

3.2.1.2 WEATHER FACTORS

Environmental factors such as weather parameters can play a significant role in reducing the effects of the enemy's surveillance capability across the visible, infrared and millimeter wavelength regions of the electromagnetic spectrum. Table 1 bears this out.

Table 1: Environmental Factors on Signature Propagation

Weather Parameters	Visible Near IR	Short Wave IR	Mid Wave IR	Long Wave IR	Milli Meter Wavelength
Low Visual	Severe	Moderate	Low	Low	None
Rain/Snow	Moderate	Moderate	Moderate	Moderate	Moderate/Low
High Humidity	Low	Low	Moderate	Moderate	Low/None
Fog/Cloud	Severe	Severe	Moderate/ Severe	Moderate/ Severe	Moderate/ Low
Phosphorus & Dust	Severe	Severe/ Moderate	Moderate	Moderate	Low/None
Fog Oil & Smoke	Severe	Moderate	Low	Low	None

In essence, the effects on electromagnetic signature propagation resulting from environmental factors are as follows: The visible, near and short wave infrared energy and millimeter wavelength regions are little affected by high humidity. The mid-wave and long-wave infrared energy is affected little by fog, oil and smoke and low visibility. The millimeter wavelength energy (radar) is affected little to none by all the defined weather parameters. However, the visible to millimeter transmissions are substantially attenuated by a) precipitation, b) fog or cloud, and c) phosphorus and dust.

3.2.1.3 HUMAN EYE RESPONSE FILTER

The unaided human eye is considered the baseline detector and solar response filter of the observer. It can be used in conjunction with optical augmentation equipment to enhance situational awareness in the battlefield environment.

A highly developed sensitivity of the eye is its ability to detect a minimal difference in luminance. This difference is called contrast sensitivity or liminal contrast. This minimal luminance difference or glint to background contrast ratio, as experienced by the observer, would describe a locus of points where the specular reflection is barely discernible, based on the range of glint reflection angles off of the reflecting surface.

Because the eye is considered a visual response filter (Appendix A, Sec 1.1.2), we are concerned about human visual response to photo-spectral stimuli, although any detector can be considered as a response filter in a surveillance system. Since psychological stimuli and responses are involved when visually interpreting, it is necessary to look at the photometric response of the eye to the radiant flux density transmitted from a reflecting source to the observer. To this end, the eye visual response to a stimulus is a gaussian shaped spectrally integrated phenomenon covering the 400-700 nanometer bandwidth.

4. GLINT HAZARD REVISITED

As previously stated, the dismounted soldier's risk of revelation to the enemy can increase in proportion to the number of solar glint reflections observed by the enemy off of optical surfaces of equipment that soldiers carry. Given this condition, the risk level will be further influenced by the size of the observer threshold domain (observation space of reflecting source), which will be a function of active energy source, solar environmental conditions, surface reflectivity optics, surveillance and counter surveillance technologies, scintillation modulation, and soldier movement. The availability of evolving active and passive electronic surveillance technologies to the enemy will substantially improve signature definition within an expanded threshold domain, thus reducing the time required for soldier detection and identification.

Given that the risk of revelation and subsequent consequences to the soldier on the battlefield will be continuously increasing over the near to mid-term, the reduction of signature size and resolution is required. This need is being met by installing anti-reflection devices and applying anti-reflection coatings to all optical surfaces of equipment in question without seriously reducing functionality. In addition, overall signature reduction technologies are being developed and applied to reduce the soldier signature in general.

A further examination of glint hazard focuses on the impacts of, visual domain, active and passive surveillance, sensor perceptibility and discriminability, counter-surveillance, and soldier location significance.

4.1 VISUAL DOMAIN IMPACTS

If the air is dry with minimal particle dispersion and the reflecting surface has high reflectivity properties, the glint visual threshold domain will be extended. This means that the observer will be able to see glint reflections further out from the reflecting source over the range of reflection angles, thus giving the observer a greater range of visual detection. Under these conditions, the probability of enemy detection will increase at specific observer-reflector distances, which may result in reduced levels of soldier survivability. As noted earlier, glint was observed at several kilometers in the desert during the 1990 Gulf War as a point source by the unaided eye during daylight.

As the threshold domain increases with the soldier at a designated distance from an observer located within the visual domain, the probability of detection increases per length of detection time, or, given a probability level of detection, the detection time would decrease. As previously discussed, detection time is that elapsed time it takes to detect a target against a background after the target region was initially exposed to observation. This was depicted in the U.S. and U.K. Glint Field Trial results using the ORACLE Model conducted in the summer of 1997 at an electro-optics range in Malvern, U.K. where glint visual domain differences were established due to optical property differences in the two eye armor reflecting surfaces used (Appendices B & C; Figures C7 and C8). Additional considerations that would further reduce detection time by an observer within the glint threshold domain are soldier movement and level of glint scintillation caused by atmospheric turbulence.

Soldier movement and scintillation modulation of the glint reflection are additional hazards that will add to the enemy detection capability of the soldier and further increase detection probability within a given time interval.

4.2 ACTIVE AND PASSIVE SURVEILLANCE

The optical enhancing devices and sensors that read the signature intensity and optical cross section across the visible-to-infrared-to millimeter wavelength regions are numerous. However, the unaided eye can only read glint reflections as intensity images against a background level of intensity within the 400 to 700 nanometer region of the spectrum. The sensors are tabulated in Table 2 as follows:

Table 2: Image Sensor Types Per Wavelength Band

Visible	Near Infrared	Middle Infrared	Far Infrared	Microwave
- TV Camera - Eye - Star Light Scope - Goggle - Ladar - Laser	- TV Camera - Ladar - Image Converters - Star Light Scope - Goggle - Laser Range Finder	- Thermal Imagers	- Thermal Imagers	- All Weather Sensors - Radar

The enemy surveillance threat posture, which directly correlates with enhanced situation awareness, is becoming critically important to counter due largely to the ever-increasing types and numbers of sophisticated sensors listed in Table 2 that are in enemy hands.

4.3 SENSOR PERCEPTIBILITY AND DISCRIMINABILITY

The levels of sensor perception and discrimination are defined as; a) detection, b) recognition, c) identification, and d) ability to discriminate between the target and its decoy. Perception or discrimination is defined as a function of the probabilities of a reflecting source being detected, recognized, identified, and determined to be a real target rather than a decoy. An example of recognition is the ability to determine whether a target is a soldier or civilian. If the target is a soldier, the ability to identify would describe whether the soldier is infantry, artillery, medic, etc. To further differentiate whether the identified target is friend, foe, or decoy requires a level of discrimination.

Table 3 gives estimates of the relative resolution required of any surveillance scanning sensor, including the human eye, for various levels of target perception or discrimination. Assume distance between sensor and target and viewing time are held constant for each case when applying the levels of perceptibility and discrimination. Table 3 depicts that given a level of detection as a baseline, it will be 4 times as difficult to recognize the target, 7 times as difficult to identify it, and at least 10 times as difficult to successfully discriminate the target.

When applying the relative resolution levels of a soldier target, either day or night, if the soldier is outside the scanning sensor's (including the human eye) resolution capability, the level of perceptibility would go no higher than the detection level since the optical signature discernment of the reflected energy would appear as a point source. Once the observer-soldier distance is within the resolution limits of the scanning sensor, then the levels of perceptibility depicted in Table 3 would roughly apply. The soldier would need to be interpreted as friend or foe, in addition to his threat capability. In other words, the optical cross section of the glint, if any, and nonglint-reflecting source could be resolved at the discrimination level, depending on the solar environmental conditions relative to the scanning sensor used, to include daytime, nighttime, terrain, weather. The process of target identification and discrimination would be easier when the scanning sensor is an active three dimensional imaging penetrating laser radar operating in the visual, infrared and microwave regions, since speckle (spots) and noise will be filtered out of the reflecting optical signature, making the target more discriminating and resolvable.

Table 3: Estimates of Relative Resolution Required of a Scanning Sensor Viewing Stationary Objects[6]

Levels of Perceptibility/Discriminability	Relative Resolution Required
Detection	**1**
Recognition	**4**
Identification	**7**
Discrimination	**10[(a)]**

(a) This value is for a low fidelity decoy

The detection level indicated in Table 3 is the baseline level, when considering the relative resolution levels of detection, recognition, identification and discrimination as part of the target identification and discrimination process. Also, solar environmental and manmade (obscurant) conditions will influence the level of target perceptibility attained by the observer.

Using the relative perceptibility measures in Table 3, when considering moving objects, detection may be 10 times easier than scanning stationary objects. However, each successive level of target perceptibility isn't necessarily 10 times easier then the corresponding levels associated with a stationary object.

The detection, recognition, identification and decoy discrimination capabilities of the sensors listed in Table 2 cover a corresponding range from 'fair' to 'very good', with continuous improvement in these areas to take place in the near to midterm years as sensor technology advances[7].

Reducing the soldier signature through changes in the optical properties of the soldier's clothing and equipment, using glint and nonglint antireflection and absorption technologies, will go a long way to protecting the soldier's location in the battlefield environment. In addition, appropriate use of active counter sensors, deception (decoys) and target blending with background will further reduce the possibility of detection and discrimination of the soldier's location.

4.4 THE IMPACTS OF SOLDIER REVELATION

The dismounted soldier revealed to the enemy through a glint reflection can increase the chances of becoming a casualty, subject to the uncertainty of the enemy's threat capability and intentions. Four opposing force battlefield conditions affecting opposing force mission objectives are defined and presented in Table 4:

A. The soldier's location is known to the enemy and is significant to the enemy.
B. The soldier's location is known to the enemy but is insignificant to the enemy.
C. The soldier's location is unknown to the enemy and is significant to the enemy.
D. The soldier's location is unknown to the enemy but is insignificant to the enemy.

Note: When the soldier's location is known to the enemy, the soldier has been detected, recognized, identified and is discriminated as not being a decoy of some type. When the soldier's location is unknown, the soldier hasn't been detected by the enemy. When the soldier's location is considered significant by the enemy, it is because it poses a significant threat to the enemy or his mission objectives, as opposed to the soldier's location being an insignificant threat to the enemy. The position may be mobile and stationary or either. The hazard of revelation (HR) and no hazard of revelation (NHR) impacts to the soldier, considering the four conditions, are defined in the third and fourth columns of Table 4.

Table 4: Enemy Knowledge of Soldier Location and Significance Including Hazard of Revelation Impacts

	Significant	Insignificant	HR	NHR
Known	A	B		A,B
Unknown	C	D	C	D

Reemphasizing the previous paragraph, if the location of the soldier is known to the enemy, as identified by interface conditions 'A' and 'B' in Table 4, the hazard of revelation is nil and the soldier would be subject to the intentions and threat capability of the enemy, based on the mission of the enemy. Likewise, if the soldier's location is insignificant and unknown, as identified by 'D', the hazard of revelation would be practically nil driven by the insignificance of the soldier's position. However, if the soldier's location is unknown and significant as identified by interface condition 'C', the hazard of revelation would be high. If the soldier's location is revealed to the enemy under the 'C' conditions, the soldier would then be subjected to the revelation hazard of the threat and intention uncertainty of the enemy, based on the transition from 'C' to 'A' where the soldier's location is known and significant.

5. RELATIVE CONTRIBUTIONS OF SURVEILLANCE TECHNOLOGIES

What are the relative evolving contributions of glint observations, and the gamut of present and evolving land, air and space platform-based surveillance equipment to soldier situation awareness, given the fact that antireflection technologies (antireflection devices and coatings) are in the process of being applied to all dismounted soldier optical surfaces? It is logical to say that glint would probably contribute insignificantly to the overall situation awareness of the soldier in a battlefield environment, given the condition that the enemy considers the soldier's location significant and unknown.

One must seriously consider the fact that during the near to mid-term, hand-held infrared and visual 3D range imaging laser radar will probably be in enemy hands. If the enemy is a first world country source, he will probably have air and space remote sensor surveillance platforms. The technological improvements are in the resolution capability of 3D range imaging measurements that contain more information than signature intensity images, which typically include large amounts of speckle and noise. Maximum ground range estimates will exceed 20 kilometers. However, the range and resolution capability of laser, and other devices such as millimeter radar, visual and infrared imaging operating on air (remote piloted and piloted vehicles) and space platforms will be much greater.

Day-night high humidity is the only weather parameter (Table 1) that will minimally influence laser signature propagation in the visual and infrared region of the electromagnetic spectrum. All the other weather parameters will have a moderate to severe effect on laser radar signature-induced propagation. The laser radar device would operate most favorably in a low humidity dry desert environment.[8]

The microwave radar is another signature definition source used during surveillance activities. It too is capable of operating in excess of 20 kilometers (kms) using a ground based platform. While operating as an air platform, its signature ranging distance will far exceed 20 kms. Future designs will include a 3 dimensional imaging capability for signature definition. The weather parameters that moderately affect microwave radar[9] induced signature are rain, ice, snow, fog and clouds. This means that microwave radar should be operationally effective in all other weather environments.

Other evolving sensor imaging and enhancement devices (Table 2) operating as passive ground, air and space-based platforms within the visual through far infrared range under the right environmental conditions will significantly contribute to the enhanced situation awareness of the soldier.

The fact that can't be overemphasized is that the major powers have active and passive surveillance equipment mounted on ground, air, and space platforms that will become more advanced over time due to technology development, transfer and sales of evolving sensor technology applications. It is also logical to say that as one progresses down the ladder of countries in terms of relative economic and military power, that countries at these respective levels will have progressively less resources and thus less surveillance technologies to apply on the battlefield. The caveat to the latter statement is if major adversaries have strategic interests with countries of less stature that want to carry on limited scale conflicts with the United States or other friendly countries. Such examples would be a) Russia supporting Bosnia, or b) Russia and China supporting Syria, Iran, and Iraq.

Previous isolated instances of significant glint hazard revealed by the unaided eye could always occur on the future battlefield under the right conditions. The probability of isolated occurrences would be most favorable in dry desert conditions. Yet, if antireflection and other signature reduction technologies are used on all optical high reflection surfaces of equipment and other gear carried by the dismounted soldier, the solar glint condition will be significantly reduced to a negligible level while the overall signature of the soldier will be reduced, depending on the specific signature reduction technology used. As a consequence, active and passive surveillance devices operating in the visual, infrared and microwave regions will have reduced signatures to identify that would lower detection to discrimination level probabilities within a given time interval, yet will still be effective as major contributors to dismounted soldier situation awareness. It is inevitable that as surveillance technologies advance, counter surveillance signature reduction technologies and other applications will also improve.

A point to remember is that although dismounted soldier location-detection and signature definition resulting from glint reflection will, in all probability, insignificantly affect overall soldier survivability in the battlefield, the ability to minimize the glint hazard of revelation is a step in the right direction to help reduce the overall soldier signature and thus reduce the probability of detection. One dismounted soldier casualty due to the glint hazard of revelation to the enemy is one too many. Yet one detection still could lead to many losses in isolated circumstances.

6. CONCLUSIONS

1). The glint visual threshold domain where an observer can detect a glint-reflecting source provides a basis for the soldier to be at risk to revelation and casualty, the extent of which will directly vary with a) domain size, b) scintillation modulation of glint due to atmospheric turbulence, c) soldier movement, d) optical surface reflectivity properties, and e) solar environmental conditions.

2). The relative contribution of glint to enemy situation awareness of the dismounted soldier in the battlefield environment should be insignificant, although isolated incidences of glint hazard are possible as supported by isolated recorded historical incidences.

3). Elevated levels of dismounted soldier risk to revelation and casualty due to glint observations off of optical equipment reflecting surfaces vary directly with the number of pieces of smooth surface equipment carried and can be significantly reduced through the application of anti-reflection technologies. In addition, dismounted soldier signature reduction technologies will continue to improve over time to counter the glint and nonglint soldier signature surveillance hazards to help reduce soldier susceptibility to the enemy.

4). Active and passive surveillance technologies i.e. binoculars, scopes, thermal and visual enhancement sights, laser, infrared and microwave radar etc., supported by ground air and space platforms significantly improve the range and target signature identification and recognition capabilities, making these monitoring devices the major player towards enhancing the situation awareness of the soldier. Given glint anti-reflection applications, nonglint signature recognition generated by technologically evolving ground, air and space electronic surveillance equipment platforms will continue to serve over the long run as the mainstay soldier enhanced situation awareness capability.

5). Evolving sensor surveillance technologies will contribute more significantly as the major influence towards enhancing the situation awareness of the soldier due to major improvements in and applications of 3D imaging resulting with improved resolution and greater range capability.

7. RECOMMENDATIONS

1. Evaluate evolving glint reduction technologies for effective application to all soldier worn optical equipment including weaponry, eye armor and head mounted configurations.

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APPENDIX A

DEVELOPMENT OF GLINT THRESHOLD DISTANCE MODEL IN THE SPECTRALLY RESOLVED AND INTEGRATED DOMAINS

DEVELOPMENT OF GLINT THRESHOLD DISTANCE MODEL IN THE SPECTRALLY RESOLVED AND INTEGRATED DOMAINS

1. OPTICAL PATH APPLICATION THEORY

The following theory deals with discerning the basic physical concepts involved in the attenuation of the glint spectral energy signature transmitted along two optical paths defined as a) sun to ground reflecting surface to observer and b) sun to background reflecting surface to observer. This approach will provide a basis for developing a mathematical model that calculates a locus of points that define a glint visual threshold domain, based on a range of specular surface reflectivity coefficients associated with a corresponding range of solar incident angles (Figures A1 and A2). Modifications to the values of the surface reflectivity coefficients due to changes in the optical properties of the specular surface will result with a corresponding change in the glint threshold domain definition. The R(1) reflectivity coefficient values are greater than the R(2) ones in Figure A2. Thus, this model can serve as a decision-aid tool for designing specular surfaces.

The attenuation effects on transmitted solar energy along the optical paths within the 0.4 - 0.7 μm visual wavelength region will be discussed in terms of atmospheric extinction, surface reflective geometries and detector response. Reflectivity properties of a specular surface will be presented as an attenuation function that is wavelength and solar incidence angle dependent. The application of spectrally resolved and integrated concepts, using the contrast ratio of the glint-to-background spectral intensity values at various distances from the reflecting source, will be considered since contrast ratio quantification is independent of solar variation intensity.

The eye is considered as the visual response filter because we are concerned about human visual response to photo-spectral stimuli, although any detector response filter can be considered as a response filter in this model. Since psychological stimuli and responses are involved when visually interpreting, it is necessary to look at the photometric response of the eye to the radiant flux density transmitted from a reflecting source to the observer as a spectrally integrated weighting function. Narrow band pass or single visual wavelength filtering will be addressed as a spectrally resolved approach to viewing glint visual signatures.

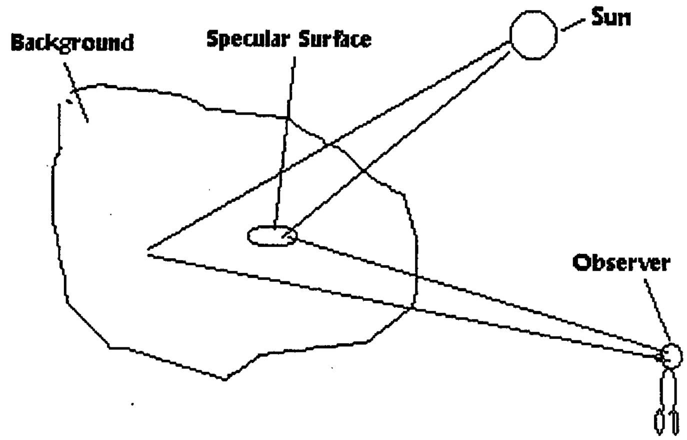
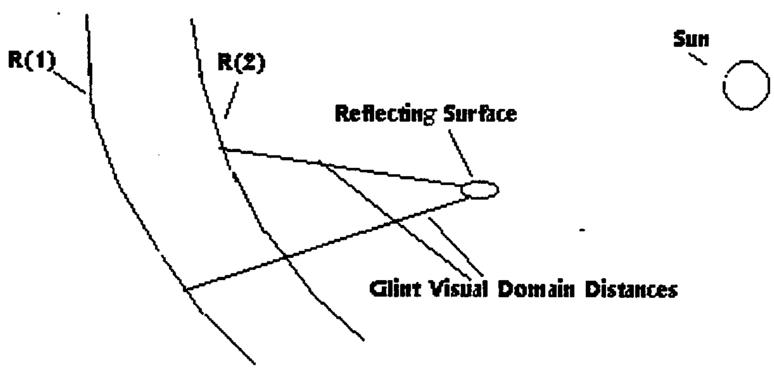


Figure A1. Sun to Specular Surface and Background Optical Paths



FigureA2 . Pictorial of Glint Visual Threshold Domains Based on Two Sets of Specular Surface Reflectivity Coefficients R(1) and R(2), Wavelength and Solar Incidence Angle Dependent

1.1 PHYSICAL CONCEPT APPLICATIONS

1.1.1 RADIOMETRIC AND PHOTOMETRIC DEFINITIONS

When undertaking the study of radiometry and photometry, we assume the existence of an instrument called a radiometer. If radiant energy is incident upon a radiometric response surface of known area and orientation relative to its direction, then radiant energy is converted to electrical energy in the radiometer as a stimulus response reaction. In the same context, the eye produces a bio-metric stimulus response reaction to radiant energy in the form of a photoelectric conversion to sight.

Radiometric quantities are physical quantities that are expressed in energy and geometrical units. For purposes of this paper the energy and geometric terms will be defined as rate of energy transmitted per unit area, which is called radiant flux density. Thus the units can be expressed as watts/cm^2. The level of radiant flux density will be equated to the level of specular or glint reflection from a mirror-like surface, such as eye armor.

The retina of the eye is a photoelectric receptor. Since perceptual response to physical stimuli is involved, the eye retinal receptor response to the visual wavelength spectrum of 0.38 - 0.74 μm could be better defined as psycho-physical. We are dealing with a photometric response to a radiometric stimuli of solar spectral energy. In this context, light is a visual aspect of radiant energy, of which the human observer is aware through the visual sensations that arise from the stimulation of the retina of the eye. Brightness is defined as that attribute of visual sensation by which an observer is aware of differences of observed radiant energy.

1.1.2 LUMINOUS ENERGY

When the human eye is used as a photoreceptor to the visual spectrum to measure the relative levels of brightness, a relative luminosity curve represented by the function '$V(\lambda)$' is produced. A standard curve of this function has been established by international agreement and may be considered the relative spectral sensitivity of the average normal, light adapted human eye. Generally, to convert the visual spectrum of radiant energy to luminous energy 'Q' according to the spectral energy function 'U_λ', we use the relative luminosity function '$V(\lambda)$' as a weighting function in the following equations:

$$Q = K_M V(\lambda) U_\lambda \qquad \text{(A-1)}$$

or

$$Q = K_M \int_0^\infty V(\lambda) U_\lambda d\lambda \qquad \text{(A-2)}$$

where K_M is a constant that determines the units for Q. This equation provides the bridge to convert radiometric to photometric units. The photopic spectral luminosity $V(\lambda)$ of the human eye as a function of the wavelength of radiant energy* is depicted in Figure A3.

1.1.2.1 LIMINAL CONTRAST RATIOS

A highly developed sensitivity of the eye is its ability to detect a small difference in luminance. This difference is called contrast sensitivity or liminal contrast. Contrast 'C' for a given set of conditions is defined as,

$$C = (L_B - L_0)/L_A \qquad \text{(A-3)}$$

where 'L_0' and 'L_B' are the object's or reflecting surface's and background luminances respectively. The luminance to which the eye is adapted is 'L_A'. When the reflecting object and background fill the field of view of the eye, 'L_A' is determined by 'L_0' and 'L_B'. When the reflecting object and background illuminated areas are approximately equal in size, then, $L_A \cong 1/2(L_B + L_0)$. (A-4)

If the size of the reflecting or luminous object is small compared to that of the background, which is true regarding the eye armor reflecting surface to background size ratios, then the eye adaptation response approximates the background illumination

$$L_A \cong L_B. \qquad \text{(A-5)}$$

* Erickson, Ronald, China Lake Report: "Visual Detection of Targets", China Lake, 1965

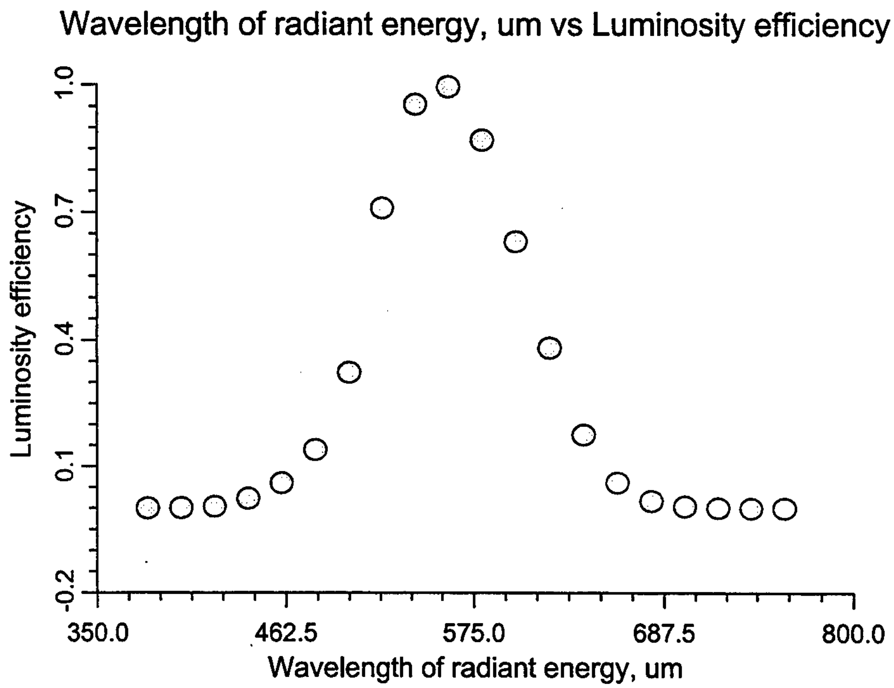


Figure A3. Spectral Response of Eye

1.1.3 EMISSIVITY, REFLECTANCE, ABSORPTANCE, TRANSMITTANCE

Emission, reflection, absorption, and transmission of radiant (solar-spectral) energy are often treated as surface phenomena. In reality, these phenomena exist when radiant energy interacts with a surface of any physical body. A true blackbody, by definition, absorbs all incident radiant energy. However, a non-blackbody is defined as having an absorbtance ratio '$\alpha(\lambda)$' of the absorbed to incident energy with a value less than unity. This means that the balance of the energy is reflected and transmitted.

Let us assume that a non-blackbody reflecting object having an absorptance '$\alpha(\lambda)$' less than unity, is placed within an ideal blackbody cavity. According to the principles of thermodynamics, the object will reach the temperature 'T' of the cavity and remain at this temperature. At this equilibrium condition, the spectral irradiance at the object surface is equal to the spectral emitted radiance '$M_\lambda(T)$' derived from Planck's Radiation Law as the energy flow rate per wavelength per unit area of a blackbody surface. Yet the power absorbed by the object will equal '$\alpha(\lambda)M_\lambda(T)$'. The remaining power must be apportioned to transmission and reflection. If the object is assumed opaque, the amount reflected can be quantified using the expression $[1 - \alpha(\lambda)]M_\lambda(T)$. Because an object is generally in equilibrium with its surroundings, it must emit as much energy as it absorbs '$\alpha(\lambda)M_\lambda(T)$' to satisfy Kirchhoff's law. Emissivity '$\varepsilon(\lambda)$' is defined as the ratio of the energy emitted by the surface compared to the energy emitted by an equal area of a blackbody surface at the same temperature.

At the surface of an object where radiant energy at wavelength 'λ' is incident upon the surface, a fraction '$\alpha(\lambda)$' is absorbed, a fraction '$\rho(\lambda)$' is reflected, and a fraction '$\tau(\lambda)$' is transmitted. For most materials, the radiant absorbing value '$\alpha(\lambda)$' is almost constant with change in incidence angle. But the wavelength dependent reflecting and transmitting radiant energy rates per unit area will change with incidence angle, based on the nature of the optical characteristics of the materials. Because energy must be conserved we have:

$$\alpha(\lambda) + \rho(\lambda) + \tau(\lambda) = 1. \qquad \text{(A-6)}$$

The reflection may occur at the surface by either specular (glint) or diffuse reflection, or it may return from within the material by scattering if the material is a translucent, non-homogeneous medium.

In summary, the incident, reflected, and emitted energy must be considered external to the object surface. Internal to the object surface, there is absorbed, transmitted, and scattered energy.

Based on the reflectivity characteristics of an optical specular surface, a statistical nonlinear fit using a 5th degree polynomial can depict a reasonably accurate statistical relationship between normalized reflection values and solar incidence angles. This mathematical relationship can provide a basis for estimating glint threshold distances in a glint threshold domain simulation model over a range of solar incidence angles to a reflecting surface, based on Snell's law to high reflectivity surfaces*.

1.1.4 ATMOSPHERIC EXTINCTION EFFECTS

There are three atmospheric processes responsible for the attenuation of transmitted optical images and electro-optical energy such as solar glint. They are 1) aerosol extinction, 2) molecular absorption, and 3) turbulent distortion (scintillation and beam wander). Light propagating through the atmosphere is not only scattered and absorbed by aerosols and molecules, but the wave fronts are deflected and distorted by turbulence.

The extinction has several components: molecular scattering and absorption $[j(\lambda)=j_1(\lambda)+j_2(\lambda)]$ and aerosol scattering and absorption $[l(\lambda)=l_1(\lambda)+l_2(\lambda)]$. The extinction parameter values correlate to the loss of light energy as it is scattered out of the beam or absorbed by the molecule and particulate constituents of the atmosphere during transmission. A combination of Bouguer's and Beer's laws can theoretically quantify the level of absorption of transmitted radiant energy '$\Phi(\lambda)$' over a distance 'R_0' based on the nature of the absorption and scattering medium $[k(\lambda)=j(\lambda)+l(\lambda)]$ and wavelength of the original transmitted energy '$\Phi_0(\lambda)$' using the following expression,

$$\Phi(\lambda) = \Phi_0(\lambda) \exp[-k(\lambda)R_0]. \qquad \text{(A-7)}$$

*Williams C.S., Bechlund O.A., "Optics, A Short Course For Engineers and Scientists", Wiley Inter-Science, New York, 1972

The distortion and tilt of image wave fronts by atmospheric turbulence is represented by 'C^2_N'. We can write 'C^2_N' as a function of temperature 'C^2_T' and water vapor '(C^2_Q)' turbulence parameters as follows:

$$C^2_N = (79x10^{-6}P/T^2)^2(C^2_T + 0.113\ C_{TQ} + 3.2x10^{-3}\ C^2_Q) \qquad \text{(A-8)}$$

where 'P' is the pressure in millibars, 'T' the absolute temperature, and 'C_{TQ}' the temperature humidity co-spectral structure function parameter. The refractive index parameter 'C^2_N' can be derived in three ways: 1) optical measurement, 2) measurement of 'C^2_T, 'C_{TQ}' and 'C^2_Q', and 3) calculation of 'C^2_T', 'C_{TQ}' and 'C^2_Q' from bulk meteorological data made up of water temperature, air temperature, humidity and wind speed.

The total extinction ($\alpha + \beta$) can be measured optically by determining the reduction in beam intensity over some suitable optical path. The separate components can be calculated from meteorological data. The molecular extinction values can be extracted from a LOWTRAN model and database developed by the Air Force Geophysics Laboratory (Selby et al., 1978). The aerosol extinction can be calculated from the aerosol spectral density 'N(r)', as follows;

$$\alpha = \int_0^\infty 2\pi r^2\ E(n,\lambda)\ N(r)\ dr \qquad \text{(A-9)}$$

where r is the particle radius, E(n,λ), the total scattering efficiency at wavelength 'λ' and refractive index 'n'.

2. BACKGROUND

The application of an imaging detector, i.e. eye, Charged Coupled Device (CCD), etc., as a device for taking glint and background reflection measurements at various distances from a specular reflecting source provides a good field trial approach towards the verification of existing contrast ratio models that use spectrally resolved and integrated applications. The delta between experimental and model projected contrast ratios over a distance from a reflecting source could be significantly influenced if the model neglects to consider the factor influences of a) ground level atmospheric extinction on solar energy propagation and b) the effects of the optical surface's reflection coefficients on the level of solar spectral energy reflecting from a surface as a function of incidence/reflection angle and wavelength.

A contrast model generally assumes the glint reflection viewed by an observer is a point source and the background an extended object. The point source application assumes that the spectral intensity decreases as an inverse square of distance. Glint to background spectrally resolved contrast ratios are independent of changes in solar brightness since the glint and background components change simultaneously.

The United Kingdom's Defence Evaluation Research Agency developed a visual glint contrast ratio model* to calculate glint contrast ratios over distances from ground reflecting sources and uses these results to feed into their detection time model.

2.1 SPECTRALLY RESOLVED RELATIVE INTENSITY

To derive the representative expression for spectrally resolved relative intensity we need to develop the relationships that describe the glint intensity viewed from a reflecting surface and from a background.

2.1.1 REFLECTING SURFACE TO OBSERVER

Assume the goggles' curved surface have radius 'r' such that its focal length is 'r/2'. The goggles will reflect sunlight into a diverging cone of half angle (D/2)/(r/2) = (D/r), where 'D' equals cone diameter at the reflecting surface. This means that the reflected cone at range 'R_0' has a radius of: $(R_0)(D/r)$.

Let the glint reflection intensity from a goggle surface $I_{gog}(\lambda) = I_0(\lambda,\alpha)R_c(\lambda,\alpha)$ where: solar intensity function is $I_0(\lambda,\alpha)$, and incident to goggle surface at angle (α), and at visual wavelength (λ). Also, the goggle reflectivity coefficient function is $R_c(\lambda,\alpha)$ at visual wavelength (λ) and incident angle (α). Then, the reflected power/unit area at range 'R_0' is defined as follows:

$$I_{gog} \text{ at } R_0 = \text{power/unit area} = [I_0(\lambda,\alpha)R_c(\lambda,\alpha)\pi D^2/4\ ]/\ [\pi R_0^2/r^2] = I_{gog}(\lambda)r^2\ /\ 4R_0^2 \quad \text{(A-10)}$$

Now the sensor receives power over detector area 'A_d' but lacks the angular resolution to form a proper image of glint. Thus glint appears as a feature of the detector angular width 'θ_d' resolution. Since the perceived glint intensity as seen by the detector is equivalent to the received power divided by the angular width squared, then the perceived glint intensity at detector can be defined as 'I_{gd}'. The detector glint intensity level can now be expressed as:

$$I_{gd}(\lambda) = I_{gog}(\lambda)r^2A_d\ /\ 4\theta_d^2R_0^2 \qquad \text{(A-11)}$$

which depends on angular resolution 'θ_d' of the sensor. Since point source theory is applied, the intensity relates inversely to the square of the range or distance 'R' from reflecting source to detector.

2.1.2 BACKGROUND TO OBSERVER

The background intensity '$I_b(\lambda)$' reflects with diffuse reflectance '$\rho_b(\lambda)$' times incident solar intensity $I_0(\lambda)$ into a hemisphere over a '2π' angle. From a background of area 'A_b',

* RI Young, RC Hollins, T Holloway "Simple Model for Predicting Glint to Background Contrast Ratios, Optical Glint Studies US and U.K. Joint Venture", DERA, U.K., July 1997

the reflected intensity at range R_0 is

$$I_b(\lambda) \text{ at } R_0 = A_b I_0(\lambda)\rho_b(\lambda)/2\pi\, R_0^2 = A_b I_b(\lambda)/2\pi R_0^2 \qquad \text{(A-12)}$$

The power received by the sensor is $(A_d)(I_b)$ where the perceived detector area is defined by A_d. Since the background area 'A_b' is sufficiently large for a detector sensor to form a properly resolved image of angular size $(A^{0.5})/R_0$, then the detector perceived background intensity 'I_{bd}' can be expressed as perceived power divided by the angular width squared.

$$I_{bd}(\lambda) = [R_0^2/A_b]\, A_d A_b\, I_b(\lambda) \,/\, 2\pi\, R_o^2 = I_b(\lambda)A_d/2\pi \qquad \text{(A-13)}$$

Thus the perceived intensity of the background by a detector is independent of its angular resolution and the range between background and reflecting source, given the assumption that the diffusion reflection has a '2π' angular domain due to a flat background.

2.1.3 CONTRAST RATIO (GLINT/BACKGROUND)

We can now define the intensity of glint relative to the background as perceived by the detector, in terms of spectrally resolved relative intensity, by solving for the contrast ratio '$C_R(\lambda)$' of the previously derived expressions of glint and background reflections 'I_{gd}, I_{bd}'.

$$C_R(\lambda) = [I_{gd}(\lambda)/I_{bd}(\lambda)] = [I_{gog}(\lambda)/I_b(\lambda)](\pi r^2) \,/\, [2\theta_d^2 R_0^2] \qquad \text{(A-14)}$$

This spectrally resolved contrast ratio expression is independent of solar intensity but depends on angular resolution of detector source, distance from reflecting source, and optical reflection characteristics of background and reflecting surface. The contrast ratio calculated over distance is based on the inverse square law.

2.2 SPECTRALLY INTEGRATED RELATIVE INTENSITY

Let us consider the spectrally integrated relative intensity as perceived by a detector with a spectral response function '$f(\lambda)$'. The spectrally integrated contrast ratio 'C_I' can be expressed by combining the spectrally resolved expression '$C_R(\lambda)$' from the previous section with the integral expressions of a) solar spectral energy incident to background and glint surface '$I_0(\lambda,)$', b) background and surface reflectivity filter or weighting functions '$R_b(\lambda)$ and $R_c(\lambda,\alpha)$' and c) spectral response function of the detector '$f(\lambda)$'.

Thus the resulting expression is

$$C_I = \left[\frac{\int I_0(\lambda,)R_c(\lambda,\alpha)f(\lambda)d\lambda}{\int I_0(\lambda)\rho_b(\lambda)\, f(\lambda)d\lambda} \right](\pi r^2) \,/\, [2\theta_d^2 R_0^2] \qquad \text{(A-15)}$$

This is a useful model for ocular (eye) detection. However, the model is sensitive to solar spectral shifts caused by changes in the optical path of sunlight due to the solar elevation angle coupled with the atmospheric extinction effects.

Further analyzing equation (A-6), the average integral of $I_0(\lambda) = \int K_M V(\lambda) U_\lambda d\lambda$. Based on the application of empirical data statistical curve fitting techniques, the solar zenith and smooth surface reflectivity coefficient functions highly correlate with the respective solar elevation and solar incidence to reflecting surface span of angles using a 5th degree polynomial fit done in conjunction with the above average integral equation. The background reflection function '$\rho_b(\lambda)$' is dependent on the nature of the background while the detector filter spectral response function '$f(\lambda)$' is a weighting function whose shape is dependent on the nature of the detector response filter.

2.3 GLINT VISUAL DOMAIN MATHEMATICAL MODEL

The use of a mathematical model for accurately calculating a glint visual domain is significant for designing low reflectivity optical surfaces. This is possible by mathematically describing the attenuation of solar glint energy over the defined optical paths. An example is the atmospheric extinction effects on solar energy depicted by the solar relative intensity versus zenith angle* graph in Figure A4.

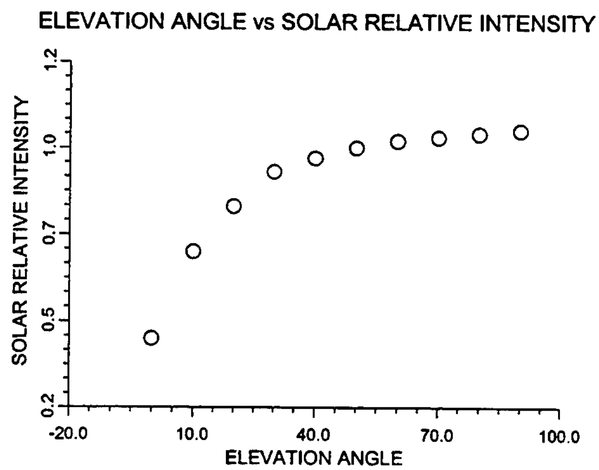


Figure A4: Atmospheric Extinction Effects on Solar Energy

Another attenuation effect results from a reflecting surface interacting with incident solar spectral energy. A general relationship between solar incidence/reflection angle and surface reflectivity coefficients is depicted for a basic eye armor surface in FigureA5.

*Kreith, Frank, Principles of Solar Engineering. Washington, DC, McGraw Hill 1978

SOLAR INCIDENCE ANGLE vs REFLECTION COEFFICIENTS

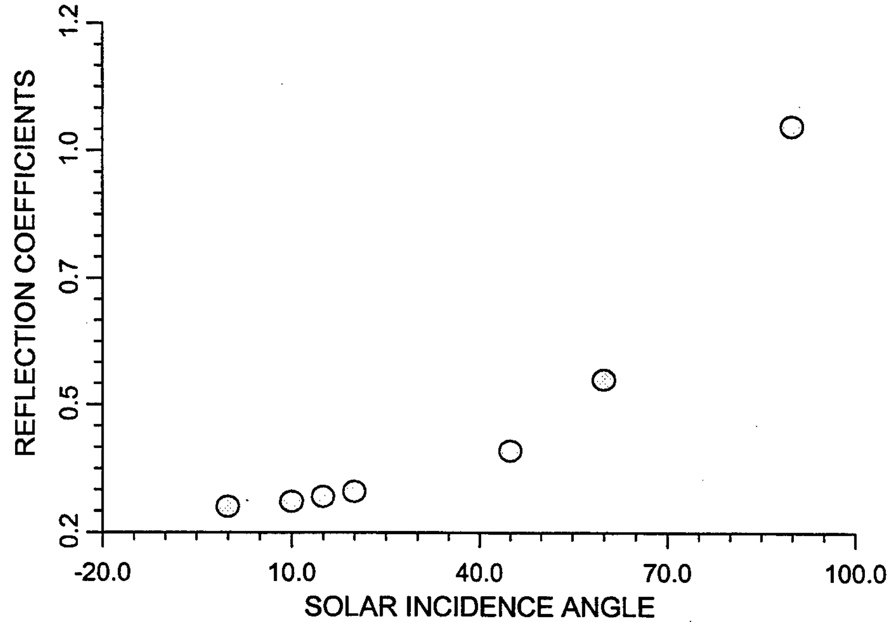


Figure A5: Reflectivity Characteristics of Eye Armor Surface

The final segment of the optical path is the atmospheric extinction effects on solar spectral energy transmitted to an observer, based on humidity and particulate levels. Atmospheric turbulence effects on transmitted solar energy are not considered.

The contrast ratio spectrally resolved and integrated expressions developed in the previous sections 1.1.3 and 1.2 will be expanded to include the effects of a) solar zenith angle function, b) surface and background reflectivity coefficient functions, and c) atmospheric extinction absorption and scattering effects.

2.3.1 SPECTRALLY RESOLVED APPROACH

The spectrally resolved contrast ratio expression can now be expressed as follows;

$$C_R(\lambda) = [I_{gd}(\lambda)/I_{bd}(\lambda)] = \frac{[I_0(\lambda)Z_c(\lambda,\beta)R_c(\lambda,\alpha)]\{\exp[-k(\lambda)R_0]\}(\pi r^2)}{[I_0(\lambda)\rho_b(\lambda)][2\theta_d^2R_0^2]} \qquad \text{(A-16)}$$

where: $C_R(\lambda)$ = contrast ratio (wavelength dependent)

$I_{gd}(\lambda)$ = goggles reflected solar intensity incident to detector

$I_{bd}(\lambda)$ = background reflected solar intensity incident to detector

$I_0(\lambda)$ = zenith solar intensity incident to background and reflecting surface

$Z_c(\lambda,\beta)$ = solar zenith angle coefficient function (wavelength and zenith angle(β) dependent)

$R_c(\lambda,\alpha)$ = normalized surface reflectivity function (wavelength and incident angle(α) dependent)

$\rho_b(\lambda)$ = background diffuse solar reflectivity function
$I_0(\lambda)\rho_b(\lambda) = I_b(\lambda)$ reflected background solar intensity
$k(\lambda)$ = atmosphere total extinction coefficient
R_0 = distance or range observer from glint reflecting source
r = radius of curvature of goggles (gently sloping)
θ_d = angular resolution or spread of detecting source

By mathematically solving for 'R_0' of equation (7), we get

$$R_0 = (r/\theta_d)\{[I_0(\lambda)Z_c(\lambda,\alpha)R_c(\lambda,\alpha)/I_b(\lambda)]\{\exp[-k(\lambda)R_0]\}\pi /2C(\lambda)\}^{0.5} \qquad \text{(A-17)}$$

By arbitrarily setting values of the following parameters as follows: a) the threshold contrast ratio '$C_R(\lambda)$' to 1.2, b) the extinction coefficient '$k(\lambda)$' to a corresponding level of humidity, c) the solar elevation angle function '$Z_c(\lambda,\alpha)$' to a solar elevation angle, d) the reflectivity function '$R_c(\lambda,\alpha)$' to cover a range of solar incidence to surface angles, and e) the detector angular resolution, a visual domain bounded by a locus of visual threshold points at ground distance R_0 from the reflecting source can be generated by solving for the range R_0. Empirically fitted polynomial expressions can be used to evaluate the solar zenith and surface reflectivity coefficients, based on the corresponding solar elevation angle and range of reflecting surface solar incidence angles used.

Changing the reflecting surface's optical characteristics would result in changes in the size and shape of the generated visual threshold domain.

On perfectly clear days the extinction coefficient '$k(\lambda)$' approaches zero in value such that the exponential expression has a value of one. If there are varying levels of humidity, then the range R_0 would have to be solved iteratively.

The advantages of using this approach is that the equations more accurately describe the basic physical phenomena of the optical path.

As with the application of any contrast ratio concept, the field trial verifications would be generally independent of the energy intensity level fluctuations but depend on detector source's angular resolution. The intensity decreases as the inverse square of range. Regarding the reflecting surface geometry, the reflecting surface effective radius of curvature is the square root of the product of the radii components.

2.3.2 SPECTRALLY INTEGRATIVE APPROACH

We can use the spectrally integrative approach even though the contrast ratio is sensitive to spectral changes such as diurnal spectral shifts. The expression would be an integral over the 0.4 - 0.7µm eye photo visual region of the solar spectrum of the previous spectrally resolved expression.

It is expressed as;

$$C_I = \left[\frac{\int I_0(\lambda)Z_c(\lambda,\beta)R_c(\lambda,\alpha)f(\lambda)d(\lambda)}{\int I_0(\lambda)Z_c(\lambda,\beta)\rho_b(\lambda)f(\lambda)d(\lambda)}\right]\{\exp[-k(\lambda)R_0]\}(\pi r^2) / [2\theta_d^2 R_0^2] \quad \text{(A-18)}$$

where: $I_0(\lambda)$ = zenith solar intensity (wavelength dependent)
$Z_c(\lambda,\beta)$ = solar elevation angle function (wavelength and zenith angle dependent)
$R_c(\lambda,\alpha)$ = surface reflectivity function (wavelength and incident angle dependent)
$\rho(\lambda)$ = background diffuse reflectivity function
$k(\lambda)$ = atmosphere total extinction coefficient
R_0 = distance or range observer from glint reflecting source
r = radius of curvature of goggles (gently sloping)
θ_d = angular resolution or spread of detecting source
$f(\lambda)$ = detector spectral response function

We solve the spectrally integrated expression equation (A-9) for threshold distance R_0 from the reflecting source as we did with the spectrally resolved equation (A-7).

Values are arbitrarily set for the parameters, like we did when using the spectrally resolved equation, as follows: a) the threshold contrast ratio '$C_R(\lambda)$' to 1.2, b) the extinction coefficient '$k(\lambda)$' to a corresponding level of humidity, c) the solar elevation angle function '$Z_c(\lambda,\alpha)$' to a solar elevation angle and corresponding coefficient value, d) the reflectivity function '$R_c(\lambda,\alpha)$' to cover a range of solar incidence to surface angles and corresponding surface reflectivity coefficients, and e) the detector angular resolution.

Regarding optical path evaluation, we integrally average the incident solar spectral energy function at zenith to obtain the solar luminosity incidence value, i.e., 140,000 candles/cm2. We evaluate the solar zenith angle and surface reflectivity coefficients using the corresponding known and 'empirically fitted' 5th degree polynomial equations.

The product of the solar zenith incidence energy '$I_0(\lambda)$', solar zenith angle coefficient '$Z_c(\lambda,\beta)$' and the range of surface reflectivity coefficients '$R_c(\lambda,\alpha)$' yield a range of glint surface reflection values 'I_{gog}' that are further attenuated by the atmospheric extinction effects on the glint signature propagated over the distance to observer. The filter weighting function '$f(\lambda)$' and the angular resolution 'θ_d' of the detector determine the detector response to the incoming glint and background energy.

The background spectral energy incoming to the detecting source is the product of the incident to background surface solar spectral energy '$I_0(\lambda)Z_c(\lambda,\beta)$' and the background diffuse reflectivity function '$\rho(\lambda)$' attenuated by the atmospheric extinction effects.

A visual domain bounded by a locus of visual threshold points at ground distance R_0 from reflecting source is generated.

2.3.3 MODEL APPLICATIONS

This model can be converted to a software package and used as an optical surface design tool by allowing the user to evaluate how changes in the optical characteristics of reflecting surfaces will impact on the size and shape of the glint visual threshold domains.

The model accurately interprets the attenuation of transmitted solar energy along its optical path thus enhancing realism as a decision aid tool for surface design.

2.3.4 FUTURE CONSIDERATIONS

The effects of atmospheric turbulence on glint may be evaluated in the future by modeling gaussian shaped glint noise scintillation modulated to a continuous wave glint signature. There is a potential need to generate and verify significant differences in the observer's signature acquired detection times at a reasonable probability of detection level between gaussian and non-gaussian glint signatures at various observer distances from reflecting source over a range of glint reflecting surface to background contrast ratios. For example, detection time surfaces representing different nongaussian to gaussian signal to noise ratios can be generated where detection time is the dependent variable and reflecting surface to background contrast ratios and distance are the independent variables.

A key question that must be answered is "under what combat scenerio circumstances does glint hazard become significant enough to compromise the mission"? If there are circumstances, "what range of significantly different gaussian minus non-gaussian glint values located within the glint threshold domain would contribute to the glint hazard"?

APPENDIX B.

DATA SPREADSHEETS

GLINT FIELD TRIALS, MALVERN, U.K.

Table B.1 Dielectric Stack Cylindrical Lens Data Using 670 nm Filter

DIELECTRIC STACK CYLINDRICAL LENS EYE ARMOR DATA
(Narrow Band Pass 670 nm Filter)

Trial No.	Range (meters)	Neutral Density	LUX (reflected)	Contrast Ratio	Peak Signal	Air Temp. Degr (C)	Relative Humid(%	Dew Point Temp(C)	Air Press. (mb)	Wind Vel. (m/s)
1	1100	1	1119	9.5	163	24	45	11.3	966	1.65
2	1100	1.3	900	4.6	35	24	45	11.3	966	1.65
3	1100	1	660	2.9	35	24	45	11.3	966	1.65
4	1100	1.3	1100	8.9	89	24	45	11.3	966	1.65
5	1100	1.3	1199	10.7	73	24	45	11.3	966	1.65
6	1100	1.3	1195	15	126	24	45	11.3	966	1.65
7	1000	0	1000	off scale	255	24	45	11.3	966	1.65
8	1000	1	1300	11.5	143	24	45	11.3	966	1.65
9	1000	1	1289	3.82	62	24	45	11.3	966	1.65
10	900	0	1060	off scale	offscale	24	45	11.3	966	1.65
11	900	1.3	900	25.7	113	24	45	11.3	966	1.65
12	900	1.3	1082	11.5	85	24	45	11.3	966	1.65
13	900	1	1150	3.82	71	24	45	11.3	966	1.65
14	800	1	800	22	255	24	45	11.3	966	1.65
15	800	1.5	850	34.2	178	24	45	11.3	966	1.65
16	800	1.5	1050	32	152	24	45	11.3	966	1.65
17	800	1.5	1023	22.8	91	24	45	11.3	966	1.65
18	800	1.5	1057	25.3	101	24	45	11.3	966	1.65
19	800	1.5	1047	off scale	offscale	24	45	11.3	966	1.65
20	800	1.5	950	21	1	24	45	11.3	966	1.65
21	800	1	500	13	13	24	45	11.3	966	1.65
22	700	1.5	1030	30	156	24	45	11.3	966	1.65
23	700	1.5	1090	off scale	offscale	24	45	11.3	966	1.65
24	700	1.5	1025	34	186	24	45	11.3	966	1.65
25	700	1.5	1030	32	82	24	45	11.3	966	1.65
26	700	1.5	1015	66	239	24	45	11.3	966	1.65
27	650	1.5	984	15.7	85	24	45	11.3	966	1.65
28	650	1.5	975	saturated	255	24	45	11.3	966	1.65
29	650	1.5	950	20	117	24	45	11.3	966	1.65
30	650	1.5	1010	17	77	24	45	11.3	966	1.65
31	650	1.5	1005	21	114	24	45	11.3	966	1.65
32	650	1.5	1050	off scale	246	24	45	11.3	966	1.65
33	650	1.5	1057	48	258	24	45	11.3	966	1.65
34	600	1.5	1032	43	255	24	45	11.3	966	1.65
35	600	2	1031	off scale	offscale	24	45	11.3	966	1.65
36	600	1.5	980	39	175	24	45	11.3	966	1.65
37	600	1.5	980	19	75	24	45	11.3	966	1.65
38	600	1.5	950	realign	185	24	45	11.3	966	1.65
39	600	1.5	950	29	86	24	45	11.3	966	1.65

Notes:

1). No correlation between the light meter lux readings and peak signal level. Lux of light meter varied too quickly to be coordinated with CCD readouts.

2). Neutral Density equals optical density across CCD camera.

3). Contrast ratio equates to brightness of reflecting surface to background.

4). Peak Signal equals photoelectric conversion in CCD camera using binary octal bit scale (0 - 255).

5). Large proportion of data variability is unwanted type.

6). Meteorological data located in columns 7 -11represents average values taken within time interval of 11:52 - 15:54 of day 9 during which glint trials were executed.

Table B.2 Spherical Lens (U.K.,ABLES) Eye Armor Data Using Visual Spectrum Filter

SPHERICAL LENS EYE ARMOR DATA
Visual Spectrum Filter

Trial	Range (meters)	Neutral Density	LUX (reflected)	Contrast Ratio	Peak Signal	Air Temp. (C)	Relative Humid(%	Dew Point Temp(C)	Air Press. (mb)	Wind Vel. (m/s)
1	20	1	880	saturated	256	22.3	57.4	13.4	970	1.65
2	20	2.3	1100	42	109	22.3	57.4	13.4	970	1.65
3	20	2.3	930	45	107	22.3	57.4	13.4	970	1.65
4	20	2.3	840	48	105	22.3	57.4	13.4	970	1.65
5	20	0	n/a	saturated	256	19.6	75.8	16	963	3.5
6	20	1.5	n/a	12	152	19.6	75.8	16	963	3.5
7	30	1	1190	saturated	256	22.3	57.4	13.4	970	1.65
8	30	2	1120	8.3	114	22.3	57.4	13.4	970	1.65
9	30	2	1094	8.4	114	22.3	57.4	13.4	970	1.65
10	30	2	1215	10.4	123	22.3	57.4	13.4	970	1.65
11	30	2	n/a	45	136	19.6	75.8	16	963	3.5
12	30	0	n/a	saturated	256	19.6	75.8	16	963	3.5
13	40	1	840	saturated	256	22.3	57.4	13.4	970	1.65
14	40	2	930	5.2	76	22.3	57.4	13.4	970	1.65
15	40	2	1005	5.4	84	22.3	57.4	13.4	970	1.65
16	40	2	985	5.2	82	22.3	57.4	13.4	970	1.65
17	40	0	n/a	saturated	256	19.6	75.8	16	963	3.5
18	40	1.5	n/a	11	131	19.6	75.8	16	963	3.5
19	50	1	n/a	6	166	19.6	75.8	16	963	3.5
20	50	0	n/a	saturated	256	19.6	75.8	16	963	3.5
21	50	1	1015	saturated	256	22.3	57.4	13.4	970	1.65
22	50	2	790	3.9	44	22.3	57.4	13.4	970	1.65
23	50	2	930	3.9	50	22.3	57.4	13.4	970	1.65
24	50	2	828	4.2	51	22.3	57.4	13.4	970	1.65
25	60	1	1158	saturated	256	22.3	57.4	13.4	970	1.65
26	60	2	1234	3.4	66	22.3	57.4	13.4	970	1.65
27	60	2	1177	3.7	70	22.3	57.4	13.4	970	1.65
28	60	2	1178	3.3	59	22.3	57.4	13.4	970	1.65
29	60	1.5	1045	2.4	153	22.3	57.4	13.4	970	1.65
30	70	1	1070	1.6	229	22.3	57.4	13.4	970	1.65
31	70	1	1125	1.5	229	22.3	57.4	13.4	970	1.65
32	70	1	1136	1.4	221	22.3	57.4	13.4	970	1.65
33	70	1	1089	1.43	214	22.3	57.4	13.4	970	1.65
34	75	1.3	n/a	4	58	19.6	75.8	16	963	3.5
35	75	0	n/a	saturated	256	19.6	75.8	16	963	3.5
36	85	1.3	n/a	4	67	19.6	75.8	16	963	3.5
37	85	0	n/a	saturated	256	19.6	75.8	16	963	3.5
38	95	0	n/a	saturated	256	19.6	75.8	16	963	3.5
39	95	1.2	n/a	5	100	19.6	75.8	16	963	3.5
40	100	0	n/a	saturated	256	19.6	75.8	16	963	3.5
41	100	0.3	n/a	1.2	160	19.6	75.8	16	963	3.5

Notes:

1). No correlation between the light meter lux readings and peak ht meter signal level. Lux of light varied too quickly, coupled with lag time between lux and CCD readouts.

2). Neutral Density equals optical density across CCD camera.

3). Contrast ratio equates to brightness of reflecting surface to background.

4). Used photopic response filter with spherical eye reflector.

APPENDIX C.

ANALYSIS AND RESULTS OF U.S. AND U.K. GLINT FIELD TRIALS

ANALYSIS AND RESULTS OF U.S. AND U.K. GLINT FIELD TRIALS

The United States and the United Kingdom conducted a set of glint field experiments during the summer of 1998 under the Army Operations Research Information Exchange Agreement IEA-A-A-96-1448 to help determine, amongst other objectives, if glint reflecting off of eye armor significantly raises the soldier vulnerability detection level. The following results and analyses were generated.

1 EXPERIMENTAL APPROACH

The reflecting source to background contrast ratio measurements were taken over a range of distances from the Natick cylindrical dielectric stack and U.K. spherical (Ables) reflecting surfaces using a CCD image detection system. The measurements were taken over several days at the 1.2 kilometer laser optics range in Malvern, U.K., during the early 1997 summer months as weather conditions permitted. Virtually all the data was taken from 1100 to 1800 hours each day the glint trials were executed. The level of humidity was not considered as a controlling factor because the execution of the trial runs was primarily influenced by a wet summer season in the U.K. Therefore, atmospheric extinction coefficients could not be derived from the data taken, which was one of our objectives. Typical reflectance spectra is depicted in Figure C1 covering spectra for grass as a background source, and dielectric and ballistic goggles as glint reflecting sources.

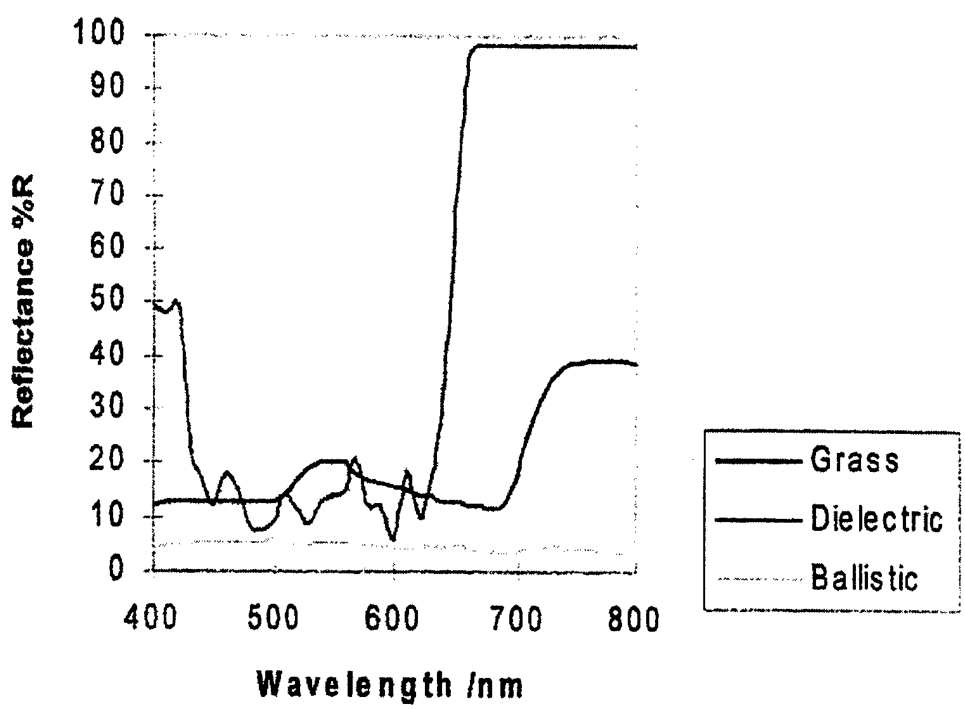


Figure C1: Reflectance Spectra Covering Grass, Dielectric Goggles, and Green Ballistic Goggles

Spectrally resolved and integrative techniques were used to generate glint to background contrast ratios derived from solar intensity measurements taken by a charged coupled device fixed gain imaging detector at various distances from the reflecting eye armor sources during humidity varying sunny days. The eye armor reflecting sources used for the field trials were the U.S. Army M-40 outsert dielectric stack cylindrical system and the U.K. tri-stimulus laser protective spherical system. Along with the use of neutral density filters, a 670nm narrow band pass was used in conjunction with the cylindrical reflecting surface while a eye visual range filter (0.4-0.7um) was used with the spherical reflecting surface to accommodate the detector's dynamic range. For the unaided eye, the extent of the visibility of solar glint is derived for each reflecting surface.*

2 RESULTS

The large variability in the cylindrical lens data depicted in Table B-1 in Appendix B, taken at the respective distances from the cylindrical reflector by the detector was primarily due to the low level atmospheric turbulence effects that became more pronounced over the distance the glint signal traveled. Each day that measurements were taken offered slightly different environmental conditions, which affected the level of scintillation in terms of distortion and tilt of the glint spectral energy wave front relative to the background reflection energy. Since the detector takes an instantaneous picture reading of the glint and background signature intensities, each ridden by a gaussian shaped spectral noise frequency, a minimum threshold number of readings needed to be taken at each measured distance to normally distribute the data spread in order to nullify the effects of scintillation or modulated wave-front distortion.

The cylindrical surface graph in Figure C2 depicts the relationship between contrast ratio and distance from cylindrical reflecting source and shows the effects of atmospheric turbulence. The average contrast ratio at 1100 meters is about 10. Because of the large random variation in the residuals, it was impossible to apply any curve-fitting techniques to predict a 1.1 contrast ratio threshold distance with any degree of accuracy. However, if we apply equation A-8 or A-9 identified in Appendix A: sections 1.3.1 and 1.3.2 respectively, the threshold distance would be in the 2500^+ meter range.

* 1) WJ Chevalier and B Kimball "Glint Field Trial Results and Application to Glint Threshold Distance Algorithm", U.S. Army Soldier System Command, Technical Report, Natick/TR-98/016, March 1998
2) RI Young, RC Hollins, T Holloway, "Optical Glint Studies" DERA/EL/03C73/TR97360/1.0, Farnborough Hampshire, UK, January 1998

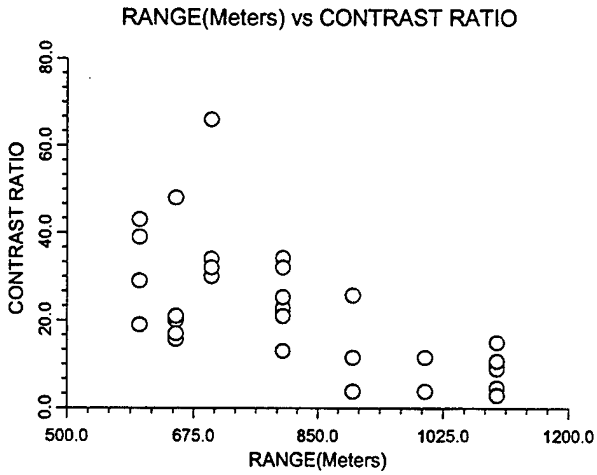


Figure C2: Cylindrical Surface

The projected visual threshold using a 1.1 contrast ratio is in the 2500 to 3000 meter range, based on the use of equation A-7 in Appendix A given low to moderate humidity atmospheric extinction effects, as depicted in Figure C3 below.

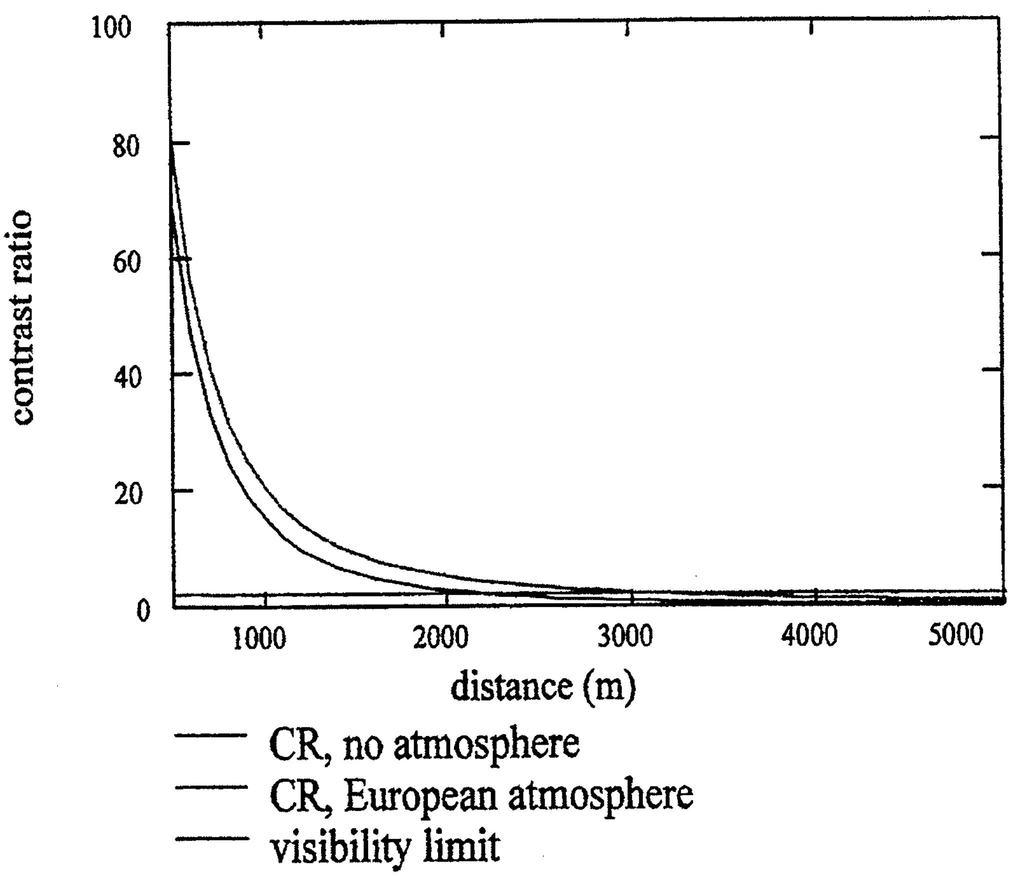


Figure C3: Calculated Contrast Ratio Curves for Cylindrical Goggles with and without Atmospheric Attenuation

When taking measurements using the spherical reflecting source, the operators of the imaging detector used a photo-visual eye response filter. When examining the spherical lens data in Table B-2 in conjunction with Figure C4, we see little variability in the data taken at the respective distances from the spherical reflector because the data were taken over a 100 meter distance. Thus the atmospheric turbulence had little effect on the propagating glint signature.

The average contrast ratio at 100 meters was measured at 1.2. The projected visual threshold contrast value of 1.1 for the spherical reflecting surface calculates to be at about 200 meters, based on the application of the Bleasdale-Nelder statistical model $[Y=(A+BR)^{-1/C}]$. For example, using the spherical lens data in Table B-2 and applying the statistical model to generate a reasonable good curve fit, the resulting curve fit equation is estimated to be

$$Y = \text{Contrast Ratio (CR)} = (-.008989 + .00488\text{Range})^{-1/1.2768} \qquad \text{(C-1)}$$

Setting the Contrast Ratio to 1.1 which is close to the visual threshold value, the range calculates to be about 200 meters. See curve fit in Figure C5.

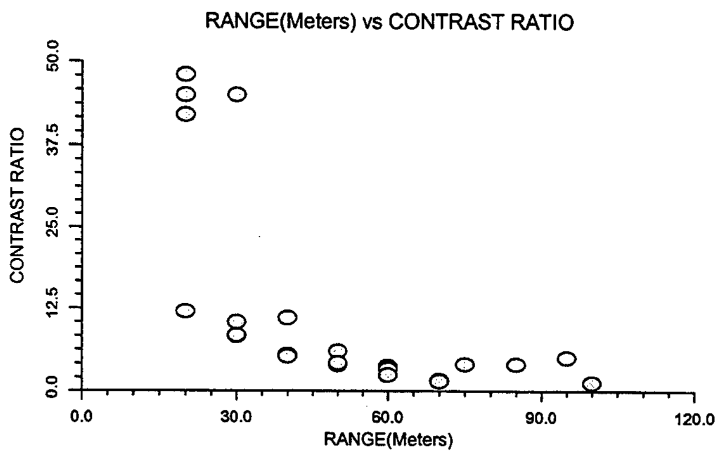


Figure C4: Spherical Surface

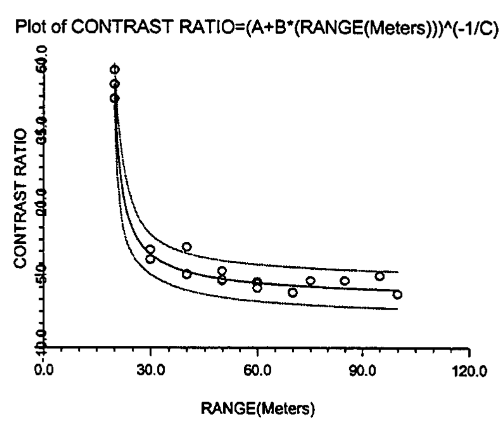


Figure C5: Spherical Surface: Contrast Ratio Versus Range

The surface geometry and reflectivity optics differences of the spherical (Ables) and cylindrical (dielectric stack) surfaces indicate that the cylindrical surface contributes to a much larger glint threshold distance of about 2500 meters from reflecting surface. This is based on projected calculations given that the measured contrast ratio is 10 at 1100 meters. As mentioned, the spherical surface contributes to a glint threshold distance calculation of 200 meters and a measured average contrast ratio of 1.2 at 100 meters. See photo-visuals in Appendix E.

Although the radii of curvature of both surfaces are similar in value, the optical surface properties of the dielectric stack cylindrical surface offer much higher reflectivity coefficients over the range of reflection angles then do those of the spherical surface# (Ables). The other contributing factor is the fact that the cylindrical surface has one radius of curvature compared to two for the spherical surface. This means that the spherical surface initiates a two dimensional divergence of the reflecting glint signature, which corresponds to reflected glint intensity correlating inversely to the square of the distance. In that context, the cylindrically reflected signature would have a single dimensional divergence because of the one radii, and would correlate inversely to the single power of distance. Ultimately, the rate of divergence in each case is inversely related to the square of the effective radius of curvature of the reflecting surface.

Other issues of concern that might have contributed somewhat to unwanted variability in the data include: a) background definition variations, b) control of glint incidence/reflection angle, c) measurement system versus eye spectral response, and d) operation within the dynamic range of the imaging detector.

It is very difficult to minimize or eliminate the random effects in taking the background imaging readings relative to the glint readings. Also, changes in the amount of glint reflected energy to change in incident angle become significant beyond an incidence/reflection angle of 45^0 to the reflecting surface, as evidenced by the relative luminosity versus reflection angle graph* depicted in Figure C6. These combined effects are probably more significant as distance between detector and reflecting source increases, i.e., cylindrical contrast ratio data (0-1100 meters) due to lack of control of experimental runs.

* Schmelz, Mark, "Reflections from the Sun-wind-Dust Goggles" Natick Labs, 07 May 1990, Natick, Ma.

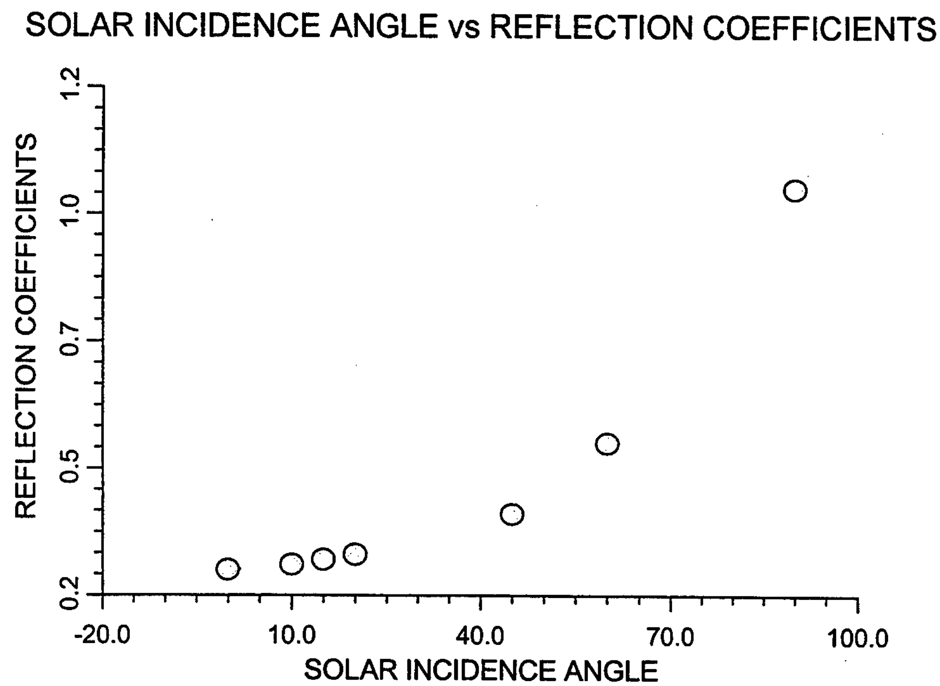


Figure C6: Normalized Reflectivity Coefficients of a Specular Reflecting Surface

It would have been ideal if an eye photo-spectral filter instead of the 670#nm filter was used while taking the cylindrical measurements, but readings were taken over a substantial distance and during the duration of the afternoons, which necessitated the use of the latter. Spectral shift occurs during the afternoon favoring the longer wavelengths, which are more efficiently reflected off the goggles.

It is absolutely necessary to operate within the dynamic range of the imaging detector to eliminate potential detector error in contrast ratio measurements. This factor alone could be a significant error contributor if some of the readings were saturated.

3 ADDITIONAL CONSIDERATIONS

If we examine the U.K. environment in relationship to the overall western European environment, the relative humidity level during the summer on the average is moderate (45-76%), as depicted in Tables B1 and B2 in Appendix B, assuming this micro-sampling of meteorological data is representative. The range of solar incidence angles over the course of the trials was 30-55 degrees, meaning that the change in reflectivity coefficients to change in solar incidence angle is small over the trials.

Regarding the cylindrical eye armor, what this means is that if the trials were run in a desert environment, the reflectivity coefficients could have been twice their value if we consider 70-85 degree solar incidence angle to normal of reflecting surface, along with the fact that the atmospheric extinction contribution would have been close to unity, all other factors being the same. See Figure A5 and Equation A-17 in Appendix A. This would account for about double the 2500 to 3000 meter range to about the 5000 to 6000 meter range in a desert environment, or the equivalence of several kilometers, such what was apparently observed off of Natick cylindrical goggles during the Persian gulf War.

Regarding the spherical eye armor reflecting surface, given that the contrast ratio is approximately 1.2 at 100 meters. Glint disappears beyond the distance of 200 meters from the reflecting source at the 1.1 contrast ratio value based upon the use of a statistical curve fit model. See Figures C4 and C5. Again, under desert conditions and using equation A-18 in Appendix A, the observer glint threshold distance would be at least 400 meters during the day.

Obviously, night time observer glint threshold domains would be considerably smaller due to the fact that the illumination levels due to the moon are approximately 6 orders of magnitude lower (100x) than under full sun lit conditions. The magnitude order would lower further depending on a) phase of moon, b) earth moon distance, and c) albedo (reflectivity).

3.1 GLINT FIELD TRIALS

One of the purposes of running the joint U.S. and U.K. Daytime Solar Glint Field Trials (Appendix B&C) was to determine visual threshold domain differences using U.K spherical and U.S. cylindrical eye armor reflecting surfaces. The cylindrical surface had much higher reflectivity properties such that glint was capable of being observed as far out as 2.5 to 3 kilometers; whereas glint could be observed off of the spherical glasses out to only 200 meters. What this means is that the cylindrical eye armor optical surface offers a much larger visual threshold range for observation. Considering the extended visual threshold domain in a battlefield environment, if the enemy is unaware of the soldier's position and the soldier chooses not to be seen, the probability of enemy detection will increase that will decrease soldier survivability probability and thus increase his probability of becoming a casualty.

3.1.1 HUMAN FACTORS APPLICATION USING ORACLE

The U.S. and U.K. Solar Glint Field trial results were based on taking radiometric measures at different distances from the spherical and cylindrical eye armor reflecting sources without considering human factors. The ORACLE model is a human factors model developed by the U.K. taking into account such parameters as; a) range, b) target size, c) contrast ratio between glint and backdrop, and d) background luminance. This model predicts the probability of seeing the glint and does this using a modified set of data. In effect, ORACLE calculates the probability of seeing a target from knowledge of the target's size and contrast ratio of target against background. This model is ideally suited to predict the visibility of a glint from our field measurements.

* R.I Young, R.C. Hollins, T Holloway, Laser Optics Group, Defense Establishment Research Agency DERA), United Kingdom

The following parameters were employed in the calculation for the ORACLE model variable set. Typical values were used for describing the observer's performance. Glimpse time was 0.333 seconds. The maximum number of glimpses used for search was 50. The glint size was seen on the goggles to be on the order of 0.005 by 0.005 meters. The glint is considered stationary, and the target intrinsic luminance contrast values which were based on the glint contrast ratio calculated at 30 meters are 10,000 for the cylindrical surface and 70 for the spherical surface. The calculations were undertaken for a typical sunny day with background luminance of 10,000 Cd/m^2, a sky to ground luminance value of 4 and visibility set at 15 kilometers.

The probabilities for observing the glint off the optical surfaces at different distances are depicted in Figures C7 and C8. For the spherical goggles the glint can definitely be seen at 70 meters, has a slim chance of being observed at 150 meters, but by 200 meters is practically invisible. Similarly, glint can be observed quite readily at 1000 meters off the cylindrical goggles, could be visible at 2000 meters, however, by 3000 meters the glint would be extremely difficult to observe with the human eye. These results for the spherical and cylindrical surfaces calculated by ORACLE correlate well with the results of the contrast ratio prediction equations A-16 and A-18 in Appendix A, and what was experienced by the observers during the glint field trials. See Glint Field trial Data, Appendix B. More data would be needed before the results would become statistically significant. Yet these results give a level of confidence for predicting what would be expected when observing glint in the field under the set of conditions associated with running the glint field trials.

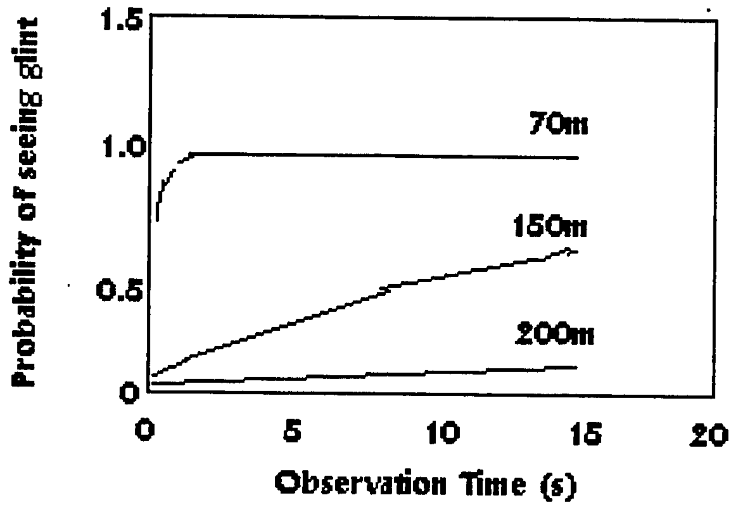


Figure C7: Probability of observing glint off spherical goggles over observation time at distances of 70m, 150m, and 200m

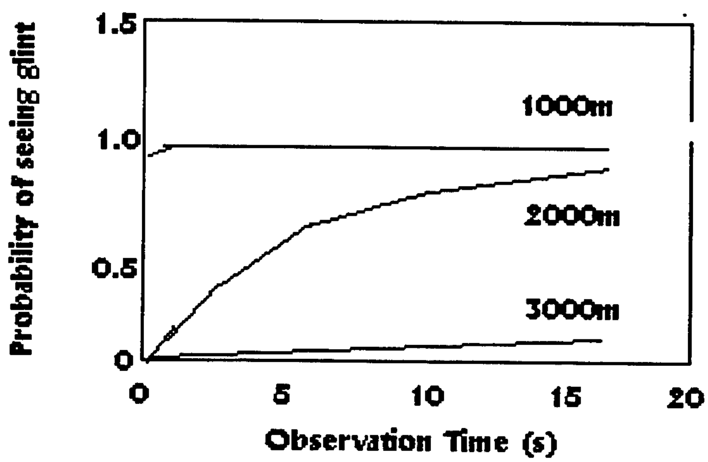


Figure C8: Probability of observing glint off cylindrical goggles over observation time at distances of 1000m, 2000m, and 3000m

3.2 DETECTION ENHANCEMENT THROUGH MOTION

The human eye visually detects a moving object more quickly than a stationary one. Analogies to this exist at other wavelengths involving active surveillance equipment. For example, a doppler radar can discriminate a 10-m^2 moving target much more easily than it can a 100-m^2 stationary object. Glint can be generated by moving the sensor relative to the target. Regarding a moving sensor, the radar cross section of a typical military truck varies from 30-m^2 to about 3000-m^2 within a very narrow field of view around the truck's broadside. This means that a radar on a moving platform which passes the truck can pick up a significant glint signal increase by a factor of 100.

In terms of detection differences between moving and non moving glint reflecting sources, the detection time would probably decrease for a moving glint source making the soldier more susceptible to being revealed and becoming a casualty prospect. [1]

3.3 SCINTILLATION EFFECTS

The unaided human eye can view an intensity image of glint as a point intensity source out to observer threshold distances that may far exceed the distances at which the observer can visualize a discernible non glint target. This is particularly true when environmental conditions are most favorable i.e., low humidity, cloudless skies, minimum particulate and aerosol dispersion, sun near zenith point, open terrain, etc.

Further affecting the glint threshold distance are the effects of levels of atmospheric turbulence on the glint energy transmission through the atmosphere. The energy wave front, whether single or broadband wavelength(s), is modulated at some level by randomized atmospheric noise turbulence that creates levels of scintillation which directly correlate with the levels of atmospheric turbulence. To an observer reading the reflected energy sensor results, or using his unaided eye if the reflecting energy is in the visual region, the perception response is one of twinkling.

Continuous twinkling gives a second order effect when observing a reflection and tends to lower the detection time somewhat. For example, given a specific observer distance from reflecting source and a given probability level of revealing the reflecting source, the detection time would be less than if there was no scintillation that was modulating with the glint signature intensity source. An equivalent interpretation would be when the detection time and distance between observer and reflecting source are constant, as the 'twinkling' modulation intensifies (greater twinkling amplitude) the detection probability would increase. However, increased levels of atmospheric humidity tend to lower the noise modulation or twinkling effects.[2]

3.4 RESEARCH RATIONALE

Based on a need to know, research could verify the relationships of a) glint intensity level, b) detection time, c) distance between reflecting source and observer, d) modulation intensity (twinkling amplitude/glint intensity level), and e)humidity level, given a probability level of detection. The research would be based on the supposition that given a probability level of detection by the observer at a specific distance from reflecting source, the detection time would vary inversely with the twinkling amplitude of the glint. Thus the greater the twinkling amplitude modulation of a specific glint signal strength, the smaller the detection time, which would tend to raise the probability level of detection of the soldier making him a higher casualty probability, especially if he is in a battlefield environment where he wishes not to be known to the enemy.

* 1). Brown, J. Tuck, "A Common Sense Look at Countersurveillance-A Digest for Executives" Battelle Momorial Institute, Columbus Ohio, 1975

2). * U.S. Army Research Laboratory, Survivability Lethality Analysis Directorate (SLAD), Attn: David Bromley/Stanley Peplinski (DSN 258-9273)White Sands Missile Range, NM 88002

4. CONCLUSIONS

(1) There were differences in the effects that the spherical and cylindrical reflecting surfaces and their associated optical reflectivity properties had on determining the glint visual threshold distance. Limits on the visibility of solar glint as viewed by the unaided eye were:

a) Spherical reflecting surfaces - Glint is visible with a 1.2 contrast ratio at 100 meters, but disappears just beyond 200 meters at a reflecting surface to background contrast ratio equal to 1.1.

b) Cylindrical reflecting surface - Glint is visible at 1200 meters at a contrast ratio of 10, but disappears within the 2000 to 2500 meter range.

(2) Atmospheric extinction effects on glint to background contrast ratios could not be derived. The repeated measurement glint contrast ratios generated from each reflecting surface over the respective distances considered were not nested within humidity bands due to time and weather constraints.

(3) Atmospheric turbulence created enough variation in the repeated contrast ratio measurements taken at the respective distances, particularly from the cylindrical reflecting surface, to substantially reduce any useful interpretation.

(4) ORACLE Human Factors results correlate well with the field trial results and the prediction equations.

(5) Data obtained from the glint trials are insufficient in scope to warrant researchers being able to verify and validate an existing glint threshold calculation algorithm.